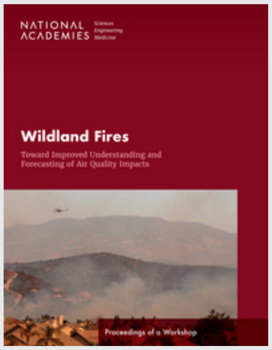

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Wildland Fires

Toward Improved Understanding and Forecasting of Air Quality Impacts

April Melvin, Rapporteur

Board on Atmospheric Sciences and Climate

Board on Chemical Sciences and Technology

Division on Earth and Life Studies

Proceedings of a Workshop

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Contents

Overview

Wildland fires pose a growing threat to air quality and human health. Fire is a natural part of many landscapes; however, climate change is increasing the extent of area burned and the severity of fires in the United States and many other parts of the world (Jia et al., 2019; Nolte et al., 2018). At the same time, humans have been expanding the "wildland-urban interface" by moving into previously uninhabited areas that may be prone to fire, and forest management has increased fuel loads in many areas. These changes heighten the risk of exposure to fire itself more broadly to fire emissions, which can travel thousands of miles and affect millions of people, creating local, regional, and national air quality and health concerns.

In September 2020, the Board on Atmospheric Sciences and Climate, in collaboration with the Board on Chemical Sciences and Technology, convened a workshop to bring together atmospheric chemistry and health research communities, natural resource managers, and decision makers to discuss current knowledge and needs surrounding how wildland fire emissions affect air quality and human health. Participants also explored opportunities to better bridge these communities to advance the science and improve the production and exchange of information. Definitions of a few key terms used during the workshop are provided in Box 1.

Wildland fire emissions are a complex mixture of chemicals that include particulate matter (PM) and trace gases emitted directly by the fire and those that form later from chemical reactions that occur within the fire plume. There is clear evidence that wildland fire smoke has negative acute health impacts (e.g., Reid et al., 2016; Xi et al., 2020). When PM concentrations are high as a result of smoke, increased mortality is observed. Links to asthma, diabetic outcomes, birth outcomes, and chronic obstructive pulmonary disease (COPD) are established or emerging, and other effects are being explored. Wildland fire smoke disproportionately affects the health of vulnerable populations including children whose lungs are still developing, the elderly, individuals with preexisting conditions, those with occupations that require close proximity to fire and extended time outdoors (e.g., agricultural workers and firefighters), and unhoused populations who may not be able to go indoors to avoid smoke. Currently, much less is known about the chronic effects and repeat exposures to smoke. Many speakers commented on the need to conduct long-term studies to expand knowledge beyond acute health effects.

BOX 1. Defining Wildland Fire and Smoke

The workshop focused on **wildland fire**, which is defined as fire that burns vegetation and other naturally occurring fuels. In this proceedings, the terms **wildfire** and **fire** are also used to refer to wildland fires. Fire **severity** refers to how hot the fire burns and the subsequent effect on the amount of biomass that burns.

Smoke refers to emissions of gaseous pollutants, hazardous air pollutants, water vapor, and particulate matter (PM). The PM portion of smoke, particularly PM ≤ 2.5 micrometers in size ($PM_{2.5}$), is commonly measured in research studies and is regulated by the U.S. Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards.

With more fires occurring within a season and across multiple seasons, the relative amount of exposure to PM ≤ 2.5 micrometers in size ($PM_{2.5}$) coming from wildland fire smoke is increasing. Exposure periods are also getting longer for individual fire events, heightening the importance of conducting more studies that can capture the types of exposure people are facing. These studies will be difficult and expensive to undertake but will provide much needed information, presenters said.

Throughout the workshop, numerous speakers highlighted the need to answer the following questions: (1) When will smoke arrive? and (2) When will smoke go away? Answers to these questions rely on atmospheric science research and are important for providing actionable information to decision makers and communicating public health risks to communities downwind of wildland fire smoke.

There are a range of tools used to forecast smoke and measure chemicals originating from wildland fire that were discussed at the workshop. At the largest scales, satellite remote sensing, often in combination with modeling, provides information on smoke location and transport used in forecasting. Measurements from aircraft provide important information about the chemical composition of pollutants near fire sources and as smoke travels away, and can also be used with satellite data to better constrain models. Many speakers noted that the complexity of constituents in the smoke, plume dynamics (e.g., vertical plume rise and boundary layer dynamics), smoke movement across complex terrain, and reconciling information across scales are key challenges for which greater understanding could lead to advancements in smoke and air quality forecasting.

Ground-based monitoring networks also serve as important information sources for determining air quality. Numerous workshop speakers commented that the existing monitoring network is useful but too sparse to adequately document wildland fire smoke exposure for many communities. To address this challenge, available low-cost sensors could be distributed more broadly to fill in the gaps. Use of these sensors indoors can also inform actions to mitigate smoke exposure by allowing individuals to directly monitor the air quality where they live and take steps to improve conditions (e.g., keep windows closed or use low-cost box fans with a minimum efficiency reporting value [MERV]-13 filter).

Communicating the risks of wildland fire smoke and how to mitigate those risks requires actionable scientific information, many speakers noted. The public needs answers to questions like “Can children play outside at recess?” “Is it safe to hold an outdoor sporting event?” and “When will smoke be at its worst?” to plan their daily lives while also reducing their exposure. Tools such as the Air Quality Index (AQI) serve as a useful metric for communicating about air quality because it is simple and straightforward, but it may not provide enough information for vulnerable populations and, because of the sparse monitoring network, may not represent the conditions for all who seek guidance on how to react to smoky conditions.

Looking to the future, many speakers noted their expectations that wildland fires will have an increasingly large impact on society. Preparation and continued improvements in the science and communication of risks will likely be essential for reducing exposure and subsequent health impacts. Speakers pointed to research, political will, multidisciplinary collaborations, and robust and sustained funding to support advancement in these areas. There is progress in many aspects of this challenge. For instance, speakers discussed new collaborations that have been developed among federal, state, and local agencies and other groups to manage lands and develop and disseminate daily information about fire risks. Managers are taking advantage of available tools and information to improve forecasting, and researchers are analyzing data from recent field campaigns. New and soon-to-be-available satellite data are anticipated to provide further insights into the complexity of wildland fires, while also balancing immediate forecasting information needs.

Land management, including prescribed burning often combined with biomass thinning, can reduce the likelihood of catastrophic wildfire risk and associated air quality impacts. While it may be counterintuitive to intentionally set fires to reduce smoke exposure, multiple workshop speakers showed that prescribed burning creates substantially less smoke than wildland fires. Over time, prescribed burns and thinning conducted at regular intervals can keep fuel loads down and help to reduce the occurrence of large wildland fires. A variety of factors make this mitigation strategy challenging. For instance, public acceptance for prescribed burning and the associated smoke exposure can be difficult to obtain, although some speakers noted that this is changing as the public is experiencing longer episodes of wildland fire smoke exposure in recent years and communication about smoke and the value of prescribed fire is improving. More frequent prescribed fires also increase exposure risk to the firefighters assigned to control these burns and additional protections are needed, speakers said. Challenges associated with overcoming political barriers, building necessary partnerships among various groups at local and state levels, and securing the necessary funds for long-term mitigation have slowed implementation of prescribed burns in many areas. California was discussed by some speakers as a state that is prioritizing prescribed burning as a mitigation strategy and addressing the large fuel loads that have resulted from fire suppression over the past century.

While questions remain in both the atmospheric science and health research communities around wildland fire pollutants and health effects, speakers stressed that there is enough information available now to inform actions that will better protect people. Through continued research advancement, collaboration, and expanded communication of risks, the actions needed to lessen wildland fire smoke exposure and impacts on human health may be improved.

Introduction

Wildland fires are having an increasing impact on air quality and human health in the western United States and many other parts of the world (Jia et al., 2019; Nolte et al., 2018). Climate change is resulting in hotter, drier conditions which, combined with a history of fire suppression and a buildup of fuels in many areas, are driving more fires, larger fires, and more severe fires that burn greater amounts of fuel over longer periods. These conditions put people at risk of exposure not only to the fire itself but also to the health effects of exposure to fire emissions, which can travel thousands of miles and affect millions of people.

The increasing wildland fire problem is highly complex and interdisciplinary in research scope, yet understanding this problem is critical to mitigating smoke health risks. The atmospheric chemistry community is working to improve the accuracy of forecasting smoke as well as to understand factors influencing smoke chemistry, transport, and changes over time. These areas can be difficult to disentangle, and they rely on a variety of tools to capture various spatial and temporal scales. From the human health perspective, there is growing knowledge of the influence of smoke exposure on acute effects, which can span from respiratory to cardiac effects, to birth outcomes and others. Different degrees of vulnerability also factor into impacts. Exposure to lengthy smoke events and effects of long-term or repeat exposure remain understudied. Applying current research understanding to actions that mitigate exposure relies on actionable information and effective communication of risks.

The Board on Atmospheric Sciences and Climate, in collaboration with the Board on Chemical Sciences and Technology, convened a workshop on September 23-25, 2020, to bring together atmospheric chemistry and health research communities, managers, and decision makers to discuss knowledge and needs surrounding how wildfire emissions, or effluent, affect air quality and human health. The workshop was structured around three interdisciplinary sessions centered on current and forward-looking questions:[1]

1. **Where are we now?** This session explored the current state of the science and communication around atmospheric chemistry and transport of fire emissions, forecasting, measurement tools, and smoke health effects.
2. **Where do we want to be?** This session focused on what is needed on the ground and how that translates into primary research needs within the atmospheric chemistry and health communities to better protect air quality and human health.
3. **How do we get there?** This session explored how to improve the production and exchange of information about air quality and health effects between atmospheric and health communities and, more broadly, while looking toward future needs and capabilities for research and mitigation of health impacts.

The health implications of poor air quality from wildland fire explored at this workshop are just a few of many impacts fire has on society. Other impacts not discussed in detail include effects on water quality, climate change, and land cover, among others.

[1] See Appendix C for the full workshop agenda.

Funding for this workshop was provided by the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation through the core sponsorship provided to the National Academies of Sciences, Engineering, and Medicine's Board on Atmospheric Sciences and Climate. This proceedings has been prepared by the workshop rapporteur as a factual summary of what occurred at the workshop. The planning committee's role was limited to planning and convening the workshop. The views contained in this proceedings are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the planning committee, or the National Academies.

Wildfires and Human Health—An Overview

John Balmes, University of California, San Francisco and Berkeley, opened the workshop by providing an overview of wildfires in California and their effects on air quality and human health. Wildland fires have increased in frequency and area burned in recent years in California as well as other locations, with further increases anticipated in the future. The state typically receives snow and rain in the winter and spring, followed by hot and dry summers when fires occur; then rains begin again in October, which end the fire season. Climate change is now shifting this pattern, causing hotter and drier summers and later arrival of the rainy season, thereby extending the fire season. At the same time, drought conditions have killed hundreds of millions of trees, which serve as fuel when fires occur. A long legacy of fire suppression in the state has also contributed to a buildup of fuels, meaning that fires have much to consume once ignited.

The 2020 fire season, which was ongoing at the time of this workshop, was poised to be a record-setting year for California. Four of the five largest fires in the state's history were active, more than 3.6 million acres had burned, more than 7,000 structures were damaged or destroyed, and at least 26 fatalities had occurred. Residents had also been exposed to smoke for many weeks, compared to previous years when exposures were typically on the order of days in a single fire season.

Wildland fire emissions contain a variety of pollutants of concern for human health. Primary pollutants released directly from fire include PM, carbon monoxide (CO), nitrogen dioxide (NO_2), polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs). Balmes said that wildland fire emissions are "much like tobacco smoke without the nicotine" because both are produced by burning plant biomass. Secondary pollutants form when emissions react in the atmosphere and include PM and ozone (O_3).

Balmes explained that there is robust evidence of acute respiratory health effects from wildfire smoke exposure (e.g., Reid et al., 2016), and, more recently, links to an increase in acute cardiovascular events, including strokes, have been identified (e.g., Wettstein et al., 2018). There are also health outcomes of possible concern that researchers are examining based on what is known about exposure to $PM_{2.5}$.[1] These include effects on pregnant mothers, birth outcomes, effects on child development, metabolic outcomes like diabetes, cognitive decline in older people, and mental health concerns.

Part of protecting the public from these possible outcomes is to have those communicating with the public provide a consistent, simple message. Balmes noted that at-risk communities can be made more resilient by preparing for both the fires themselves as well as the smoke. Preparing for fires can include actions like bulldozing fuel breaks around neighborhoods, removing vegetation from around homes, and improving escape routes. To mitigate smoke exposure, residents can stay indoors and install filtration equipment while those in outdoor occupational settings and vulnerable populations can benefit from respiratory protection gear. Many of these potential actions were discussed in more detail during this workshop and are captured throughout this proceedings.

[1] $PM_{2.5}$ is commonly measured in research studies and is regulated by the U.S. Environmental Protection Agency through the National Ambient Air Quality Standards.

Where Are We Now?

To set the stage for the workshop, the first session focused on the current state of the science and communication around atmospheric chemistry and transport of fire emissions, forecasting, measurement tools, and smoke health effects. Presenters reflected on what is being learned in areas where the science is evolving rapidly and highlighted many resources and tools that have been developed in recent years to advance understanding.

The Changing Fire Regime

Jennifer Balch, University of Colorado Boulder, discussed what she views as the three primary ingredients for the changing fire regime: climate, fuel, and ignition. Hotter, drier conditions caused by human-driven climate change are strongly linked with more burning in the western United States (Abatzoglou and Williams, 2016; Balch et al., 2018; Dennison et al., 2014; McKenzie and Littell, 2016; Stavros et al., 2014; Westerling, 2016; Westerling et al., 2006; Williams et al., 2019). Although this pattern is evident, ecosystems vary in whether and how much the size and severity of fires is changing. For example, the size of fires in conifer forests in the Northern Rockies has increased by about 150% while those in the Southern Rockies/Colorado Plateau have increased by more than 400%. More generally, about one-quarter of ecosystems are experiencing an increase in fire severity, meaning that more plants are dying in those ecosystems during fire events than under previous climate conditions. Fires are also spreading in forests that do not typically burn, and ecosystem regeneration following fire may also change.

Humans are also influencing the fuels available to burn by fragmenting landscapes and introducing invasive species. Invasive grasses can double or triple fire activity across large regions, Balch said. For example, invasive cheatgrass carpets about 40,000 km^2 (almost 10 million acres) across the United States and is a "flashy fuel" that allows fire to spread quickly. Cheatgrass has been implicated in some of the largest fire events in the United States.

A third ingredient of the changing fire regime is ignition. Humans were responsible for igniting over 84% of U.S. wildland fires in recent years. Human-ignited fires occur across a larger portion of the year than lightning-ignited fires, which primarily occur during the summer. Consequently, human-ignited fires have lengthened the fire season and led to burning of fuels that are higher in moisture content (Balch et al., 2017) (Figure 1). Human ignitions also co-occur with windier conditions than do lightning ignitions.

Looking to the future, wildfire smoke is expected to be more intense and widespread (McKenzie et al., 2014; Spracklen et al., 2009; Yue et al., 2013), Balch said. Depending on weather conditions, this smoke could reach communities—60 million homes in the United States were within 1 km of a wildland fire between 1992 and 2015, and 13 million people who are also socially vulnerable live in areas of extreme fire risk (Davies et al., 2018; Mietkiewicz et al., 2020), raising equity concerns. Unlike other natural disasters that are not initiated directly by human actions, humans have the agency and power to shift the dialogue from an emergency mindset to one that is more proactive to ameliorate wildland fire disasters, Balch said.

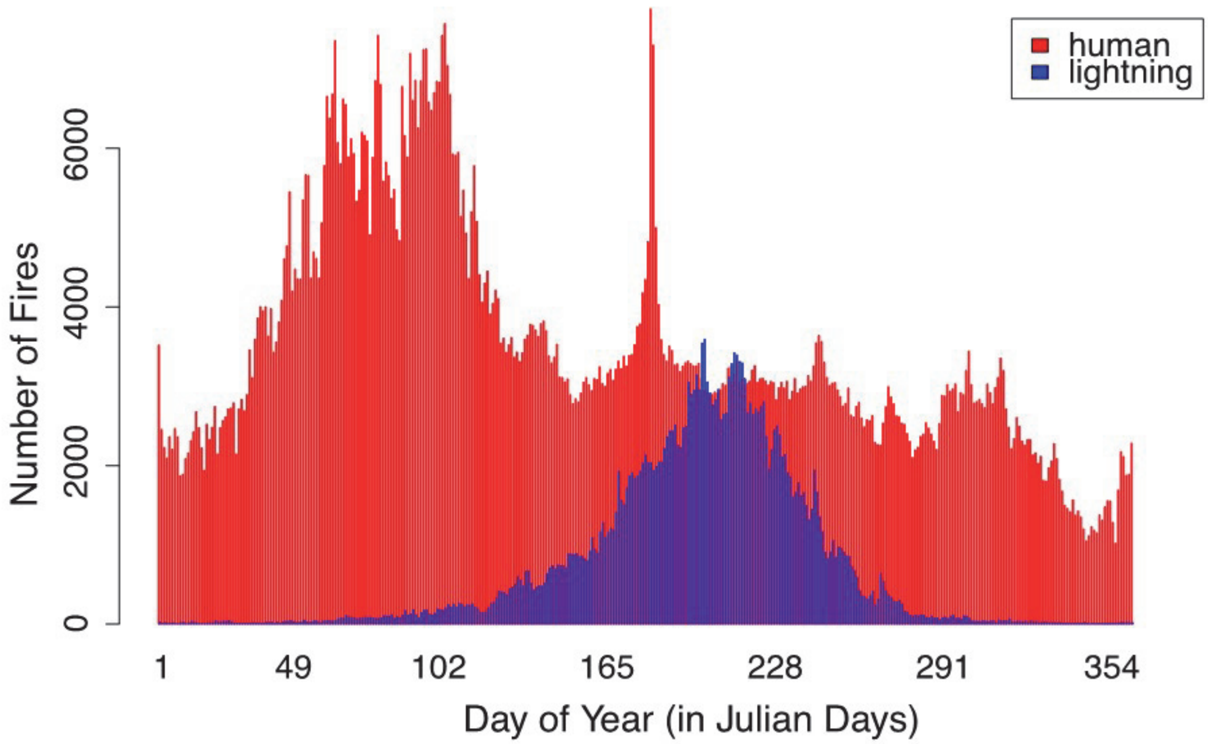

FIGURE 1. Frequency distribution of wildland fires ignited by humans (red) and lightning (blue) on each day of the year across the contiguous United States from 1992 to 2012. SOURCE: Balch et al. (2017), in Balch presentation.

Modeling Smoke Plumes

Brian Potter, U.S. Department of Agriculture Forest Service (USFS), discussed the structure of smoke plumes that come out of wildland fires and considerations when incorporating these dynamics into atmospheric models and estimating smoke transport. Fire plumes vary in their complexity, which can be modeled conceptually. The simplest model is an axis-symmetric plume with no wind and a vertical plume that mixes and spreads out when it reaches a stable layer (Figure 2a). This is most commonly observed in prescribed burns where human ignition of a fire perimeter results in the fire burning more rapidly inward than outward. When wind is added to the model, the fire and plume tilt, taking on more of a boomerang shape (Figure 2b). The ideal model for this situation is one where the plume entrains all the smoke into the updraft that then mixes and reaches a stable level. A further layer of complexity that can match what is observed in the field is to add surface burning with smoldering behind the flaming front (Figure 2c). In this case, some of the smoke is entrained into the major plume while some remains near the ground, creating a much more complex vertical distribution of smoke and variability in the horizontal and downwind transport of the plume.

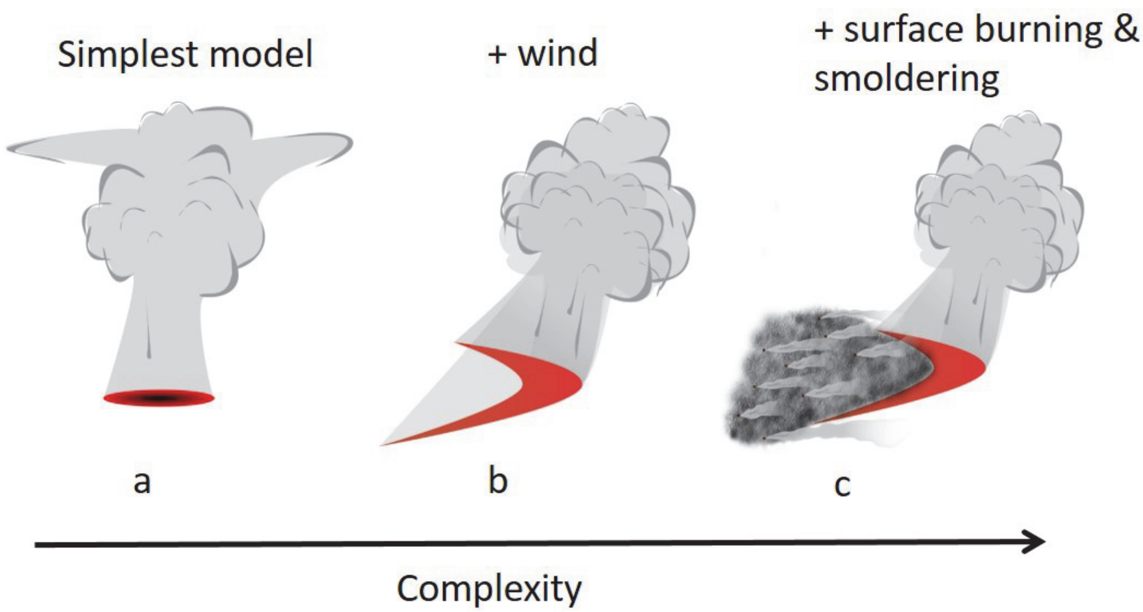

FIGURE 2. Graphical representation of advancing complexity of fire plumes, including an axis-symmetric plume (a), a boomerang-shaped plume resulting from the addition of wind (b), and additional complexity due to surface burning and smoldering (c). SOURCE: Adapted from Potter presentation, U.S. Forest Service.

There are many other complicating factors to consider when modeling plumes, Potter said. These include spatial and temporal variation in the balance between wind and heat that gives the plume buoyancy; vertical and horizontal wind shear effects on mixing; the influence of canopy structure on turbulence and vertical movement of smoke; burning area geometry and scale; and interactions among fires occurring close to one another, which may draw smoke into different plumes or create a single plume. Another consideration is whether to use a single versus multiple convective cores in the model, which has implications for how to treat vertical distribution and subsequent horizontal transport and mixing of the plume.

Potter noted that merging smoke plume models with atmospheric models requires consideration of assumptions about how the plume mixes vertically as well as with the environment as the smoke rises. It is also important to know whether the mixing assumptions are consistent among the models or whether they are redundant, overmix, or compete with one another. Additionally, the spatial scale of atmospheric models (e.g., 4-km and 12-km grid cells) and the size of the plume matter for interpretation. Most of the plume rise models in use assume that the perturbation due to a plume is small when compared to the other environmental conditions being modeled within a given grid cell. However, if a plume is large and present across a large portion of the grid cell, it may not be possible to determine whether the atmospheric model is accounting for the influence of the plume.

Predicting Smoke

Workshop panelists discussed current predictive, modeling, and forecasting capabilities for smoke, as well as opportunities for advancement in the next decade.

Ravan Ahmadov, NOAA Global Systems Laboratory and the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder (CIRES), explained how well weather forecast models, such as the NOAA High-Resolution Rapid Refresh (HRRR)-Smoke model, work for smoke transport. Smoke and air quality models estimate fire emissions using different methods to forecast smoke transport; however, all models also use fire detection data obtained from satellites. The HRRR-Smoke model uses fire radiative power (FRP) observed from satellites as an indicator for heat energy generated by fires. Emissions of both $PM_{2.5}$ and gas species can be calculated from fire radiation energy (calculated from FRP data in combination with assumptions about fire duration) and emission factors. The HRRR-Smoke model forecasts smoke (primarily PM) as a passive tracer without chemistry at high resolution (3 km x 3 km) for the contiguous United States, producing a new forecast every hour using FRP data from the previous 24 hours and forecasting up to 48 hours into the future. This includes capturing spatial gradients in the smoke distribution influenced by meteorology and complex terrain. The HRRR-Smoke model is also capable of capturing the feedback between smoke and radiation that results in dramatically reduced direct radiation reaching the surface due to the heavy smoke.

However, there are cases where the HRRR-Smoke model is not able to forecast smoke distribution in the atmosphere, Ahmadov explained. This includes situations where pyrocumulonimbus clouds develop, which occurs frequently in the western United States. There is a need to develop next-generation forecast models at fine (subkilometer) scale in order to forecast smoke, especially over complex terrain, and these models should include full O_3 and aerosol chemistry, aerosol-meteorology interactions, and assimilation of in situ and satellite atmospheric composition measurements, Ahmadov said.

Integration of Aircraft and Satellite Data into Forecast Models

James Crawford, NASA, used data from the Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) aircraft campaign to demonstrate how in situ measurements from aircraft can be used with satellite data to trace impacts of fire on the atmosphere over time and to help better constrain models. Across numerous western U.S. wildfires, a strong relationship was observed between the relative change in carbon dioxide (CO_2) analyzed from an aircraft and the FRP calculated by combining geostationary satellite data, aircraft windows measurements, and data collected downwind of the fire plume. FRP allows researchers to determine whether aircraft measurements have captured the peak of the fire and, with a time series of FRP from geostationary satellites, can be used to apportion emissions in time on a much finer timescale than is typically done in models. Crawford noted that it is still necessary to retrospectively apportion total emissions in terms of area burned and fuel consumed, but the CO_2-FRP relationship demonstrates that aircraft campaigns can bring additional information to the interpretation of satellite data. Crawford also explained that VOCs vary across fire plumes, but show a strong and predictable relationship with CO.

Reactive nitrogen species are much more variable in smoke plumes due to factors including fuel type and burning conditions. The availability of reactive nitrogen affects the secondary chemical reactions that occur and what species are present both near and downwind of the fire. For instance, nitrous acid can drive production of radicals close to the fire while peroxyacetyl nitrate (PAN) can halt reactions near the fire and enable reactions to occur much farther downwind. In contrast, when formaldehyde dominates radical production, radical-radical reactions occur and are more permanent, reducing the occurrence of reactions downwind. Additional factors that contribute to complexity in the chemistry and require more study include O_3 production, primary and secondary aerosol chemistry, brown carbon absorption, the air toxics generated in the plume, and the balance of day and night chemistry, among other factors, Crawford said. The ultimate challenge is to identify how to simplify these complexities so that processes can be incorporated into global and regional scale models.

Brad Pierce, University of Wisconsin, explained how observations from a variety of satellites can currently be incorporated into air quality forecasting models for wildfires, using the Williams Flats Fire in August 2019 as an example. Pierce first presented the integration of FRP and aerosol optical depth (AOD) data collected at 5-minute intervals by the Geostationary Operational Environmental Satellite with emissions and injection height predictions in the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) for the Williams Flats Fire in August 2019 (Figure 3). Results showed that the WRF-Chem forecast was able to capture the structure of the fire well in terms of AOD. The magnitude of aerosol backscatter and the injection height for this fire were also captured by comparing model data to observations from the High Spectral Resolution Lidar measured from a FIREX-AQ aircraft.

Polar orbiting satellites can also be used, Pierce explained. Coordinated measurements of AOD collected from the NOAA-20 Visible Infrared Imaging Radiometer Suite (VIIRS) instrument and high-resolution trace gas retrievals from the new TROPOspheric Monitoring Instrument (TROPOMI) measuring ultraviolet/near infrared captured CO enhancements in the plume from the Williams Flats Fire. Forecasting this fire plume was also conducted at coarser resolution (0.5 degree) at the global scale using the experimental version of the NOAA Unified Forecasting System Real-time Air Quality Modeling System. Pierce explained that this approach captured the AOD well, but it was only with the assimilation of measurements from TROPOMI that the model captured CO enhancements reasonably well for the Williams Flats Fire at this scale. Because wildfires are a global process and not confined to regional scales, without the data assimilation of global measurements, in this instance from TROPOMI, the smoke plume and resulting impact on air quality over North America would be underestimated.

Looking to the future, Pierce noted that there is a new geostationary constellation with aerosol measurements that includes an Advanced Baseline Imager and Advanced Himawari Imager that are coupled with VIIRS to provide a global perspective for aerosols. The same will be available for trace gases with Tropospheric Emissions: Monitoring of Pollution (TEMPO), Sentinel-4, and Geostationary Environment Monitoring Spectrometer providing hourly capabilities to look at trace gas distributions associated with wildfires that are available now on a daily time step from TROPOMI.

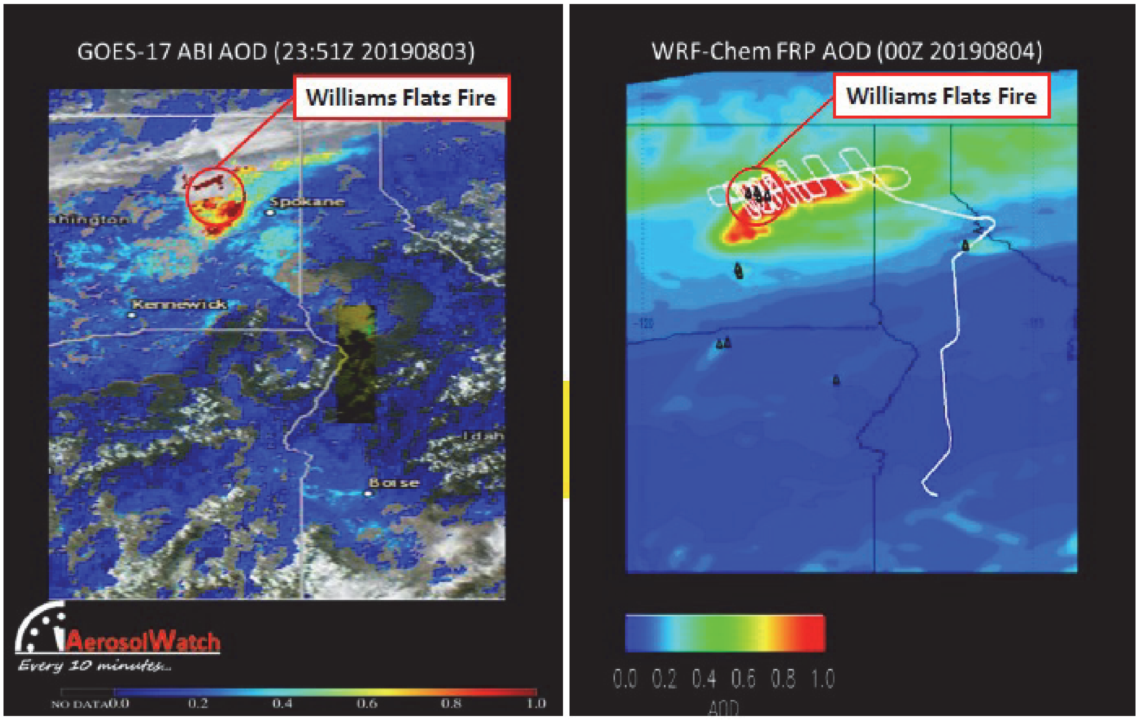

FIGURE 3. Observed and modeled information from the Williams Flats Fire. The left panel illustrates radiative power and aerosol optical depth data obtained by the Geostationary Operational Environmental Satellite, and the right panel shows that information combined with emissions and injection height predictions in the Weather Research and Forecasting model coupled with Chemistry. SOURCE: (left) Aditya Kumar, in Pierce presentation; (right) Kumar et al. (2022).

Forecasting O_3 and $PM_{2.5}$

Kirk Baker, U.S. Environmental Protection Agency (EPA), discussed how accurately models are characterizing O_3 and $PM_{2.5}$ impacts from wildfires at different scales with an aim of differentiating wildfires from other sources for regulatory assessments. O_3 produced from wildfire can vary considerably across spatial and temporal scales, with effects local to the fire and across a region. The VOCs and oxidized nitrogen gases (nitric oxide [NO] and NO_2, or NO_x) produced by wildfires are precursors for O_3 formation. Near the fire (within tens of miles), O_3 production is typically inhibited by NO emissions, which destroy O_3 faster than it can form. However, farther downwind (tens to hundreds of miles), VOCs, NO_x, and photochemically produced compounds including oxidized nitrogen like PAN produced from NO_x can lead to O_3 formation when conditions are favorable, such as warm, sunny days. Predicting O_3 production is complicated by the presence of PM in smoke, which can attenuate light and affect O_3 formation.

Models can predict high O_3 concentrations both close to the fire and much farther downwind. Baker explained that for the 2011 Wallow Fire in eastern Arizona, modeled O_3 downwind was a combination of that produced at the fire and transported and O_3 formed as a result of NO_x (created by the thermal decomposition of PAN) reactions, plus reactions of formaldehyde (a VOC). In areas where there is limited background NO_x, the decomposition of

PAN to NO_x can be a mechanism for O_3 formation. When a plume moves through an urban area with high background NO_x, such as Denver, Colorado, in Baker's example, O_3 production may be more affected by highly reactive VOCs originating from the fire or in the plume.

Baker compared O_3 and $PM_{2.5}$ model predictions with field data and found that the models perform well in replicating local- to regional-scale smoke plume transport. However, compared to routine monitoring data from rural areas, the models seem to systematically overpredict surface level O_3. Data from field studies allow for verification of key aspects of modeling wildfire, O_3 production, and $PM_{2.5}$, Baker explained. To evaluate and develop photochemical models, four aspects of the system need to be constrained: (1) location and fuel consumed and area burned, (2) emissions, (3) plume rise, and (4) plume transport and chemistry (Figure 4). While field studies may not be able to address all these aspects at the same time for the same fire, recent campaigns in particular have provided much more information that can inform which components can be improved on and whether any are compensating for one another, which could lead to misinterpretation of model output.

Some challenges of modeling both specific fires and fires over a broad region remain. It is difficult to get accurate activity data; large fires are well detected by satellites, but smaller prescribed fires are often missed in places like the southeastern United States. Baker suggested

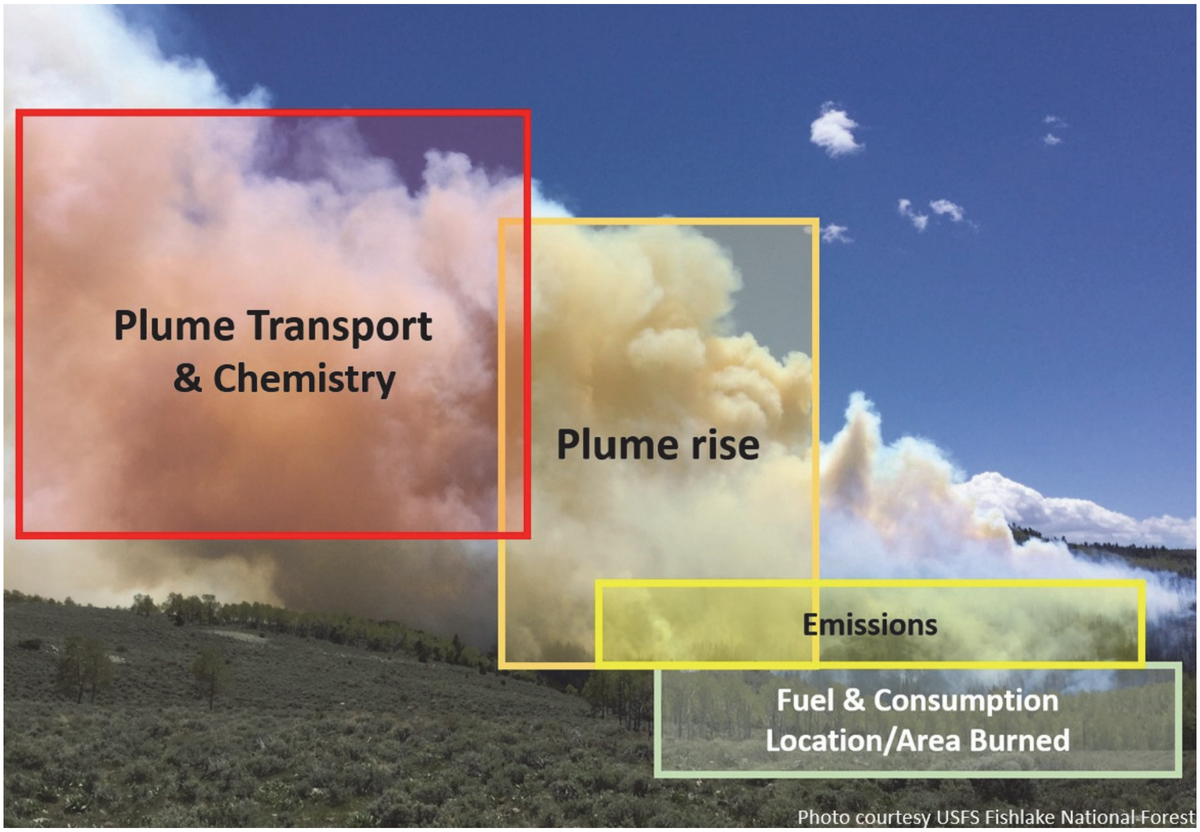

FIGURE 4. Key components of wildland fires for which better understanding is needed to improve air quality modeling. SOURCE: Baker presentation, U.S. Forest Service.

this gap could be filled by a better ground-based, bottom-up tracking system for prescribed fire activity, or satellites with more highly resolved temporal and spatial information. Another challenge is synthesizing data on combustion phase, moisture, and fuel type from field and chamber studies, and integrating the data in a manageable way in larger-scale modeling systems. Once there is enough confidence in these modeling systems, they can be used as tools to weigh trade-offs between land management techniques and wildfire impacts on air quality.

Challenges of Modeling Vertical Dynamics of Smoke

Following the presentations, panelists discussed what they think are the biggest uncertainties in forecast modeling. The modeling of vertical distribution and vertical mixing of smoke plumes was raised by all of the panelists as a major challenge, which has direct implications for human health given that pollutants near the Earth's surface can be inhaled. Smoke plumes are extremely complex, and current models rely on traditional meteorological and weather forecast models for vertical mixing, which do not adequately capture variation in the altitude at which the plume is released, the buoyancy, effects of smoldering versus flaming fires, and other factors, Ahmadov explained. Crawford noted that plume rise is very concentrated in the atmosphere whereas the downward motion of smoke is very diffuse, which is difficult for models to capture. Baker added that it can be difficult to disentangle which processes are influencing vertical dynamics at a given time.

For the role of satellite observations in addressing vertical distribution uncertainties, Pierce explained that satellites currently do not provide vertical information about plumes, but future ultraviolet aerosol retrievals (e.g., TEMPO) will provide some information about the height of the aerosol layer and insights into whether the aerosol layer is in the boundary layer or aloft. Satellites have limited ability to provide information about plume structure, Pierce said, particularly in terms of boundary layer dynamics relevant to surface air quality for health, and that is where ground-based sensor data are needed.

The importance of ground-based sensors to collect information on vertical structure, and their use more generally for air quality modeling and monitoring, was discussed. Baker explained that EPA's Photochemical Assessment Monitoring Station (PAMS) sites will have ceilometers that measure cloud height and thickness in the future, which will provide information on vertical structure. PAMS sites will also be instrumented with Pandora spectrometers, which measure trace gases including O_3, NO_2, and formaldehyde throughout the atmospheric column. Other data sources such as the AirNow near-real-time AQI (Box 2) and the PurpleAir Network also provide useful information, which could be used to improve spatial representations of real-time air quality that could inform choices such as when to spend time outside, Baker said. While many challenges remain, panelists highlighted new instruments, capabilities, and data that may help to better constrain models and improve air quality forecasting in the future.

BOX 2. The Air Quality Index

The Air Quality Index, or AQI, is a metric developed by the U.S. Environmental Protection Agency to provide public-accessible information on the five most common and regulated air pollutants in the United States: ozone (O_3), PM ≤ 2.5 and ≤ 10 micrometers in size ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide. The AQI reports information as both a number (0 to 500) and as six categories designated by color and level of concern (from green and good for health to maroon and hazardous to health). The U.S. data that inform the AQI come from monitoring sites in more than 500 cities and can be viewed at local to national scales.

Daily AQI Color	Levels of Concern	Values of Index	Description of Air Quality
Green	Good	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Yellow	Moderate	51 to 100	Air quality is acceptable. However, there may be a risk for some people, particularly those who are unusually sensitive to air pollution.
Orange	Unhealthy for Sensitive Groups	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Red	Unhealthy	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Purple	Very Unhealthy	201 to 300	Health alert: The risk of health effects is increased for everyone.
Maroon	Hazardous	301 and higher	Health warning of emergency conditions: everyone is more likely to be affected.

AQI values and categories by color. SOURCE: airnow.gov.

Strengths and challenges of the AQI were discussed during the workshop and captured throughout this proceedings. Topics discussed include the use of the AQI as a communication tool, the representativeness of monitoring locations, and the calculations used to determine the AQI.

Combustion Chemistry

Carsten Warneke, NOAA and CIRES,[1] gave a presentation prepared by Bob Yokelson, University of Montana, on combustion chemistry and how it can be used to improve PM forecasting.

When trying to forecast PM, Yokelson has found that there are key questions related to the timing of impacts that are important to the public. Specifically, “When will it be smoky?” and “When will it go away?” There are many difficulties and major uncertainties associated with smoke production, chemistry, and exposure. Biomass burning that takes place during fires is highly complex and influenced by many factors including fuel characteristics, temperature, humidity, wind, time of day, time of year, and other chemical and physical factors, which interact in nonlinear ways that are difficult to model. Addressing these challenges alongside

[1] Carsten Warneke is currently affiliated with NOAA and at the time of this workshop was also affiliated with CIRES.

smoke health effects, including the study of metabolomics, is needed to gain a more holistic view of the impacts of smoke, Warneke conveyed.

Warneke next explained Yokelson's simplified view of biomass combustion processes and the resulting pollutants. When fresh biomass is heated, volatiles evaporate and chemical bonds in the solid fuel break, releasing toxic gases and liquid organic particles (VOCs and PM) in large quantities. These are the processes known as distillation and pyrolysis, and they produce white smoke. As the biomass continues to heat it forms char, which absorbs oxygen and releases heat during the process of gasification. Together, distillation, pyrolysis, and gasification are the processes regulating the composition of smoldering emissions, and the emissions from these processes themselves are often flammable. For instance, VOCs can reach higher temperatures and ignite, resulting in flames. Flames efficiently convert toxic pollutants to less toxic compounds like CO_2, black carbon, and NO_x and in the process provide a second heat source to drive more pyrolysis, creating a reinforcing feedback loop. Flames also play a large role in the rate of fire spread and provide buoyancy for convection, which can lift flaming and entrained smoldering emissions away from the surface, enhancing the potential for long-range transport. However, these emissions can return to the surface, often with pollutants like O_3 that form from further chemical reactions in the smoke plume. Combustion processes, their emissions, and the evolution of the smoke are measured from a variety of platforms, including aircraft, ground sites, and mobile laboratories. Wildfires most commonly produce smoldering emissions from pyrolysis or a combination of pyrolysis, gasification, and flaming. These fires are smokier than most other types of fires, including prescribed fires.

Prescribed fires during the spring and fall seasons can reduce emissions, and are also easier to forecast than wildfires, Warneke explained. Prescribed fires produce about 18 times less PM per unit of area burned when compared to wildfires (Selimovic et al., 2020). Currently, many air quality forecasting models use PM emission factors from prescribed fires, resulting in values that are lower than what is observed for wildfires. Research by Barsanti and colleagues[2] and Nergui et al. (2017) included collection of PM data from all monitoring sites in the Northwest for August 2013 and compared those data with a forecast model, which showed that under- and overprediction of PM in the model occurred in different portions of the study region. The area of overprediction suggests there is a PM loss process that is not being captured in the model. Yokelson and colleagues have investigated this loss phenomena, comparing airborne measurements at wildfire sources with downwind surface measurements in Missoula, Montana, and suggest that thermally driven evaporation of PM caused by the change in temperature between aircraft and surface altitude is causing the measured losses (Selimovic et al., 2020).

Chemistry during Smoke Transport

Emily Fischer, Colorado State University, discussed how smoke changes as it is carried away from the source, with respect to pollutants of concern for air quality: $PM_{2.5}$, O_3, and hazardous air pollutants (HAPs).

[2] See http://www.lar.wsu.edu/airpact.

Smoke is the largest contributor to $PM_{2.5}$ in the Pacific Northwest and directly downwind of this region during extreme fire years and in terms of average annual smoke exposure (McClure and Jaffe, 2018; O'Dell et al., 2020). Organic aerosols (OAs) dominate fine PM mass (Garofalo et al., 2019), and there is a relationship between emissions and subsequent chemical and physical transformations (Hodshire et al., 2019). Large, slowly diluting fire plumes generally exhibit little evaporation, which can allow for accumulation of OA, whereas smaller, quickly diluting fire plumes can lead to faster evaporation, which might decrease OA. There has been considerable uncertainty about the evolution of OA and brown carbon in wildfire plumes because of limited knowledge of precursor emissions and near-source chemical evolution. Recent work has helped to refine understanding of OA sources through the partitioning of OA into the fraction formed from direct oxidation of gas emissions and that resulting from evaporation of primary OA (Palm et al., 2020).

When looking at O_3, the presence of wildfire smoke results in an increase in O_3 on the order of 5-10 parts per billion, on average, and affects both urban and rural areas (Brey and Fischer, 2016). However, Fischer explained how different timescales and environments make it challenging to predict total O_3 production, and in order to accurately predict production there needs to be a focus on chemistry near the fire and urban chemistry downwind, as well as in the space in between. Recent airborne field campaigns including the Western wildfire Experiment for Cloud chemistry, Aerosol absorption and Nitrogen have advanced understanding of daytime chemistry relevant to O_3 production (Juncosa Calahorrano et al., 2021; Peng et al., 2020). However, while emissions from large fires can peak in the afternoon to early evening hours (Mu et al., 2011), current understanding of the ability of aircraft observations to constrain nighttime chemistry is limited but will be important for understanding the full life cycle of smoke, Fischer said.

For gas-phase HAPs in smoke, acrolein, formaldehyde, benzene, and hydrogen cyanide are likely the dominant chemicals that pose health risks (O'Dell et al., 2020). For example, heavily fire-prone regions in high-fire years such as 2018 may pose excess cancer risk from smoke mainly due to formaldehyde, the key pollutant for cancer risk. As smoke ages, the risk from HAPs decreases. Fischer noted that an important next phase of understanding HAPs will be to attribute the additional HAP burden to $PM_{2.5}$ from smoke relative to HAP abundances in urban air.

Generally, models striving to capture chemical transformations as smoke is carried away from the source have both strengths and weaknesses. The connections between aircraft observations and plume-scale models are strong (e.g., Alvarado et al., 2015). At the same time, global-scale models tied to satellite and long-term observations can be useful for identifying problems but do not yet provide solutions for modeling smoke plumes. Fischer stated that significant work is needed to move from plume-scale models to what can easily be implemented in global-scale models in order to adequately capture smoke, and simplifications in order to get at health-centric metrics may be possible.

Health Effects of Wildfire Smoke

Colleen Reid, University of Colorado Boulder, discussed the current state of understanding of various health impacts of wildfire smoke. Generally, there is clear evidence of acute effects of wildfire smoke on mortality, where days with high PM result in increased mortality above what would otherwise be expected. Several recent studies have linked wildfire smoke to diabetic outcomes (Xi et al., 2020; Yao et al., 2020). There is also very consistent evidence that wildfire smoke exacerbates asthma (e.g., Borchers Arriagada et al., 2019), and growing evidence that it exacerbates COPD and respiratory infections. There is a considerable amount of information linking cardiovascular disease to PM effects through a variety of physiological mechanisms (Brook et al., 2010), but there are inconsistent findings in the literature about whether there is an association specifically with wildfire smoke. For instance, Reid et al. (2016) found no association, whereas more recent studies have shown mixed results. Most studies have looked at acute health effects from smoke, and more work is needed to look at both longer-term episodic events and the influence of wildfire smoke on long-term health, Reid said.

There has been growing interest in how PM and air pollution affect birth outcomes, though there are only a few studies looking specifically at the role of wildfire smoke. Reid and colleagues found a small but statistically significant decline in birth weight for babies whose gestation intersected with a wildfire event when compared to those that did not (Holstius et al., 2012). Other research has shown associations with birth weight, preterm birth, and possible impacts on mothers.

Reid also suggested that there is a need for more research on mental health related to smoke plumes. Most mental health studies to date have focused on people who have been evacuated, or lost loved ones or property. However, there is a growing concern about mental health impacts of prolonged periods of poor air quality and smoke when residents are advised to stay indoors for long periods of time.

When it comes to whether the chemical composition of $PM_{2.5}$ has an effect on health impacts, there is not enough evidence to suggest that PM sources differ in toxicity, according to synthesis reports from the World Health Organization, EPA, and the Health Effects Institute. Consequently, $PM_{2.5}$ has continued to be regulated by total mass (Adams et al., 2015). While there is not currently evidence that wildfire $PM_{2.5}$ and $PM_{2.5}$ originating from other sources affect health differently, recent studies have indicated that it is possible that wildfire $PM_{2.5}$ is affecting asthma more significantly than other sources (DeFlorio-Barker et al., 2019; Kiser et al., 2020), and, more generally, wildfire smoke is an increasing source of $PM_{2.5}$, particularly in the western United States (McClure and Jaffe, 2018; O'Dell et al., 2019). More research is also needed into the health implications of O_3 produced by wildfires, Reid said.

Reid suggested that more information about other health endpoints of concern is needed, as well as studies that evaluate health impacts of longer-term or episodic, repeated exposures over time. Reid also emphasized the need to investigate why there are differences in findings across health studies (i.e., underlying population health status, components of smoke, severity of outcome, study design). One example of a factor that might lead to differences in findings is how studies quantifying spatiotemporal exposure to wildfire smoke (i.e., from ground monitors, satellite observations, or models) vary considerably.

Current Communication across Health and Atmospheric Science Fields

Panelists discussed information that is currently available and communicated between health and atmospheric research communities. This included what atmospheric chemistry information is used by the health community, other available information that could be provided, and the usability of information in its current form.

Atmospheric Chemistry Information and Tools for Health Research

Nga Lee "Sally" Ng, Georgia Institute of Technology, shared information and tools that can be contributed by the atmospheric chemistry community to improve understanding of air quality and health impacts of wildfires. As discussed by previous speakers, wildfires produce a number of gases and particles that undergo oxidation and other complex and nonlinear reactions that generate a variety of pollutants. Atmospheric chemistry can provide information on sources and chemical composition, as well as link smoke composition to atmospheric loading, to quantify properties of interest for air quality and health such as particle volatility and toxicity.

The interactions between the atmospheric chemistry and health communities often happen around model output and data from monitoring networks or satellites, with a focus on how PM mass concentration relates to exposure assessments and epidemiological studies, Ng said. However, the atmospheric chemistry community can also help to develop a mechanistic understanding of cause and effect by attributing smoke constituents to their sources and ultimately linking the toxicity of smoke components to their chemical composition. Laboratory experiments, for example, can aid in the development and validation of models and can be used to look at secondary organic aerosol (SOA) formation and the resulting oxidative stress to cells from exposure to those particles. Studies have shown that oxidative stress generated by biomass burning aerosols, such as those produced by wildfires, is higher than aerosols found in urban environments.

Ng also highlighted opportunities for improvement, including quantification of wildfire emissions and understanding of transformations in the atmosphere, particularly the oxidation of VOCs and formation of SOA and O_3. This will require more long-term measurements of atmospheric compounds and opportunities to develop low-cost techniques for continuous monitoring and exposure assessment, she said. Enhanced engagement between atmospheric chemistry and health researchers, as well as more platforms for interaction, such as workshops, conferences, and funding opportunities, are needed, Ng added.

Health Community Use of Atmospheric Chemistry Information

Rish Vaidyanathan, U.S. Centers for Disease Control and Prevention (CDC), discussed how the health community uses atmospheric science information, and the format and usability of available data. Because producing atmospheric chemistry information is generally resource intensive, the health community relies on academic partners and federal agencies working in atmospheric chemistry fields to produce the data products that can then be used to quantify exposure and link to health data.

There are many health applications for highly resolved atmospheric model outputs and data products including public health surveillance, epidemiological assessments, and situational awareness and emergency response. One example Vaidyanathan provided was of a real-time smoke vulnerability assessment where an existing operational forecast of surface smoke from the National Weather Service was linked with various measures of vulnerable populations to estimate where smoke was going and the populations to be impacted. This allowed for identification of areas of interest and opportunities to alert vulnerable groups to the smoke health risks.

Vaidyanathan highlighted challenging areas for the health community as well as current research gaps. He suggested establishing a central repository for historical smoke predictions that follows data collection standards and is available in a format that is accessible to public health agencies and practitioners to use readily. Vaidyanathan also pointed to a need for smoke exposure information to be provided at a county or subcounty level, rather than grid scale, for conducting health risk assessments. Finally, he described a need for atmospheric science information and data products to support comparative assessments of smoke exposure for prescribed burns versus wildfires.

Strengthening Epidemiological Research through Greater Interdisciplinary Collaboration

Ana Rappold, EPA, discussed challenges to using air quality ground monitoring data to define exposure in health effects research, as well as opportunities to build on earlier approaches and data to improve evaluation of the public health burden from wildfire. Looking back to research from a decade ago, studies relied on monitoring data and the time period of exposure, without any additional information on the exposure. Monitors continue to be commonly located close to population centers and far away from fires, and therefore are not representative of populations with the highest smoke exposure. In addition, at high levels of smoke, the data from monitors may be uncertain and monitors can malfunction, creating data gaps. In recent years, epidemiological research has become more interdisciplinary and studies have become more complex, with higher spatial and temporal resolution. Instead of using just sparse monitoring data, studies utilize chemical transport and dispersion models as well as smoke satellite images, which allow for parameterization of population exposures on daily and subdaily timescales and over larger regions and longer time periods.

In order to represent the high level of uncertainty in these models, Rappold suggested making modeling data publicly available, using data fusion models, and making multiple exposure models accessible. Rappold also encouraged the integration of research tools such as sensors, wearable technology, and satellite data in order to improve health outcomes. Improved collaboration among research disciplines to increase the operational capacity of existing applications to better communicate health risks of smoke in real time would also be beneficial, Rappold said.

Improving Communication between Health and Atmospheric Science Experts and with the Public

Following the presentations, speakers discussed the historical focus on the health effects of PM and whether this is limiting, as well as what other constituents should be measured to improve understanding. PM serves as a proxy for wildfire smoke and while smoke contains a complex mixture of pollutants, removal of any single component would not remove all health effects. From a communications standpoint, focusing on PM sends a strong message, even if there are differences in toxicity and particle composition. Speakers noted that studying the chemical components of smoke is important, but greater consistency in what is measured across different fires would also be beneficial for determining whether other constituents should be receiving more attention from health scientists. An additional challenge for understanding health effects is quantifying the contributions of PM and O_3 from wildfires compared to their background levels.

Rappold noted that forecast models and real-time information can motivate individuals to make decisions and behavioral changes to protect their health. However, behavioral changes in response to wildfire smoke episodes are not currently enough to combat the observed health effects. There is an opportunity to communicate better with the public, for example, when populations are experiencing smoke from prescribed burns. Ng added that wildfire events are a great opportunity for outreach and engaging community (or "citizen") scientists by having members of the public measure PM concentrations inside and outside their homes, which could increase public awareness and change behavior.

The panelists agreed that building more bridges between the health and atmospheric science communities is needed. Examples for how this has been done include the NASA Health and Air Quality Applied Sciences Team, the American Geophysical Union GeoHealth Section, and the International Association of Wildland Fire's International Smoke Symposium. Panelists also pointed out that funding agencies have an opportunity to help to organize and integrate these communities by funding research that marries health effects and atmospheric sciences.

Some Session Themes

Susan Anenberg, George Washington University, summarized the first session of the workshop. Some key themes she identified across the session included the following:

- It is not what has been learned but rather what is being learned—this is a rapidly evolving area of science with many new resources and tools to expand capabilities.
- Questions about uncertainties remain and whether uncertainties are narrowing or have grown larger than previously thought based on new information. These are important considerations when trying to bound what is known about fire and smoke and links to human health, Anenberg said.
- There are many opportunities for synergy between atmospheric scientists and health scientists. There is added complexity in that there are many types of atmospheric scientists (e.g., modelers, remote sensing experts using satellite measurements, those that collect empirical measurements from aircraft campaigns), and health scientists (e.g., clinicians, epidemiologists, toxicologists). It will be helpful to provide more opportunities to bring these communities together.

Where Do We Want to Be?

The second session focused on what information is needed on the ground to better protect air quality and human health, and how this translates into primary research needs within the atmospheric science and health communities. In other words, what needs to be learned about air quality to mitigate, manage, and prevent health effects?

Protecting Public Health at the Local Level

Sarah Coefield, Missoula City-County Health Department, explained what is needed to protect public health from wildfire smoke based on her experience in a local public health department. There are a number of roles that public health officials must take on during smoke events, sometimes in collaboration with other departments or agencies, that could be improved with additional information from the health and atmospheric science communities. These roles include communicating smoke forecasts and information about how to reduce exposure, providing intervention measures, and making policy decisions (Figure 5).

To improve communications about smoke and air quality, Coefield emphasized the need to convey information about when the smoke will be present, how long it will be present, and when the air quality will be at its worst during the event. This gives the public a sense of agency and allows individuals to make plans that may lessen their exposure. It is also helpful in the current environment where public health officials are striving to provide guidance about smoke

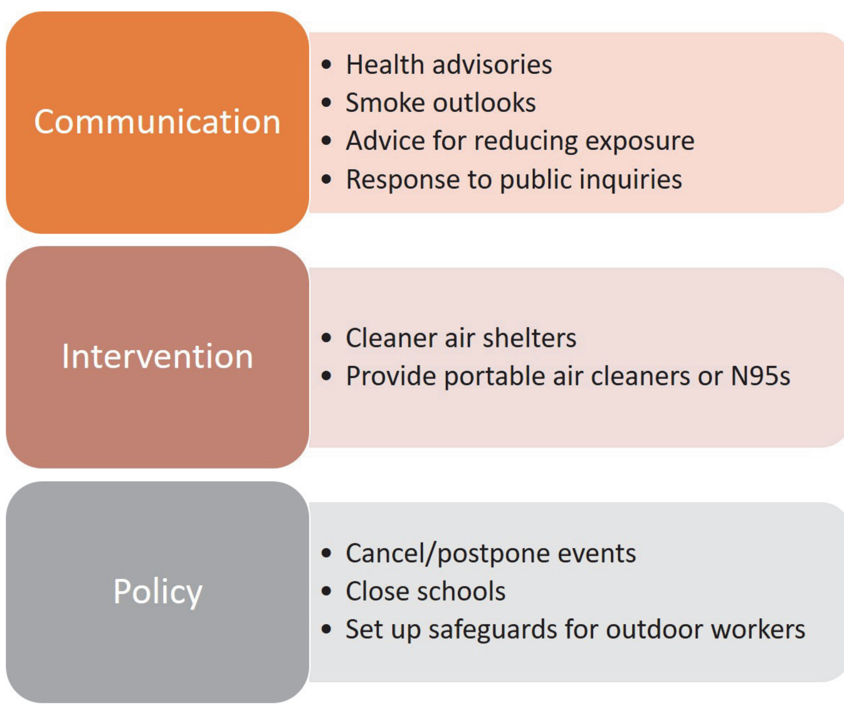

FIGURE 5. Overview of the role of public health officials in addressing wildland fire smoke events. SOURCE: Coefield presentation.

exposure alongside precautions to reduce exposure to SARS-CoV-2 (COVID-19). For instance, if school classes are held outside due to COVID-19, questions arise about the point at which outdoor smoke levels become unsafe. Models are helpful for forecasting; however, current models struggle with capturing smoke in complex terrain including small, narrow valleys in Montana where many people live. Better monitoring information is also needed, Coefield explained. In a large state like Montana, which has only 20 permanent $PM_{2.5}$ monitoring sites, many people do not live near real-time, ground-based information about their air quality and therefore must rely on information available at larger scales.

Communicating research about the health effects of smoke in a way that is actionable is also important. Highly detailed research studies are often not readily translatable to address questions about what air quality levels are safe for children to play outside or to hold a sporting event, for instance. Instead, information that can establish clear requirements is useful to move beyond providing advice and guidelines—people tend to push back against guidelines and not change their behavior. Ideally, more information about how much smoke is too much for different populations (e.g., different ages, different activities) would be valuable, Coefield said.

Improved understanding of indoor air quality during fire events is also important to protect health and inform what intervention measures could be used. Coefield explained that indoor air quality can quickly deteriorate to match that of outdoors, especially in large public buildings. Increasing the number of indoor air quality sensors in large buildings and in homes could help to understand this problem better and provide actionable information and cost-effective intervention options to improve indoor conditions and reduce smoke exposure. For intervention, it is critical to ensure that communities are treated equitably and that a sustainable funding source is available to provide the necessary equipment (e.g., N95 respirators or portable air cleaners) and to inform the public.

Finally, data-driven policy changes are needed, Coefield said. Jurisdictions could aim to handle wildfire smoke issues in a consistent manner, with comparable resources. One example is to update building ventilation standards to require filtration that traps fine PM found in smoke. The American Society of Heating, Refrigerating and Air-Conditioning Engineers is currently developing guidelines for wildfire smoke-prone areas, which could lead to updates to ventilation standards. Another example is to improve the protections for outdoor workers, many of whom are of low socioeconomic status and have additional health complications. The Occupational Safety and Health Administration (OSHA), which is tasked with ensuring safe and healthful working conditions in the United States, does not include protection from wildfire smoke.

Examples of Research Needs to Improve Understanding of Smoke Health Effects

Michael Kleinman, University of California, Irvine, discussed what information is needed to improve understanding of wildfire smoke health effects from toxicological and public health perspectives. From the atmospheric sciences, this includes information about the size of particles in the smoke plume as it ages and is transported, as well as detailed chemical characterization of the smoke over time. From the health community, Kleinman said that information on bioavailability (i.e., how the body takes up smoke toxins) from both wildland

and structural fires is needed, as well as better toxicity assessments of smoke constituents. Prospective epidemiological assessments over time that assess potential chronic consequences of repeated smoke exposure over the course of a year or years would also be valuable.

There is also still much to be learned about specific stressors (biological factors or health status) and the role of multiple stressors in impacting health risks. Some stressors are well known, but time has not been spent to isolate specific effects. Age, for example, is known to impact how people respond to air pollution, with younger people tending to have more respiratory effects and older people experiencing more cardiovascular effects. Little is currently known about the effects of exposure on developing lungs and hearts, especially in children, and there is limited information on what happens to unborn children when pregnant women are exposed to wildfire smoke. Other stressors where information is lacking include the role of gender in influencing health effects as well as the influence of mental health. Stress is known to reduce immune function, which is critical in preventing diseases and response to multiple chemical exposures. For multiple exposures, Kleinman explained that having an AQI that addresses more than one pollutant would be beneficial because there can be additive and/or interacting health effects among pollutants.

Most of what is currently known about health effects of smoke exposure come from short-term studies, meaning that the long-term risks of exposure are not well established. Kleinman noted that a major challenge to conducting long-term, prospective epidemiological studies is that it is difficult to get funding. The short-term data that are available show strong epidemiological evidence of acute effects of inhaling particles on respiratory disease, including asthma and COPD. Inhaled particles are also strongly related to cardiovascular disease associated with air pollution generally. However, the evidence connecting cardiovascular disease to wildfire smoke in particular is currently weaker. Heart disease is causally related to exposures to ambient PM, and inhaled particles and gases associated with wildfires are composed of compounds that are known to affect heart disease and cancer. Kleinman explained that much of the chemical composition of toxic substances associated with combustion-related emissions and pollution are not that dissimilar from wildfire smoke, so they may be expected to have similar health effects. As wildfire frequency and intensity increase, exposures over the long term will be a substantial fraction of annual exposure and are not taken into account in current air quality guidelines.

Smoke Mitigation and Management Needs

Panelists provided insights from on-the-ground experience working to mitigate and manage wildland fire risks, coordinate activities and make decisions, and protect occupational workers exposed to smoky conditions. This included explaining common challenges as well as some successes in getting to where we want to be.

Proactive Forest Management

Dana Skelly, USFS, described how fire suppression and climate change have affected fire regimes and the role of proactive wildland fire management. Every ecosystem that has vegetation will burn at some point; it is just a question of how often and how intensely it will burn. The success of fire suppression over the past 100+ years has created an illusion that all wildland fires can be controlled. Instead, fires are a disturbance that must be lived with and managed, much like hurricanes, floods, tornadoes, and earthquakes.

Skelly explained how past land management practices, including fire suppression, have contributed to the shift in the intensity and severity of wildland fires (Box 3). To counteract this, prescribed burns and mechanical treatments that remove fuels are used in areas that would have burned naturally in the past when suppression efforts were not implemented. This leads to the question of what it means to manage a forest enough to compensate for past practices, compounded with the impacts of climate change. Research has shown that annually only about 45% of the area that would have burned historically within the National Forest System is being treated (Vaillant and Reinhardt, 2017), meaning that the managed footprint is not equal to what historically burned. This does not allow for the decision space required to effectively provide for firefighter and public safety, reduce smoke impacts, or consider restoration options. From a mitigation standpoint, wildland fire smoke is the worst-case scenario. Prescribed burns produce less smoke than wildland fires and, in many parts of the country, less smoke than wood-burning stoves. The fire situation being experienced now is much greater than what was experienced in the past.

A Local Government Effort

John Stromberg, mayor of Ashland, Oregon, explained actions taken to protect the city from wildfire threats and the associated challenges of developing policies that balance various risks to the community. Ashland is a city that has been built into a dense forest that serves as the city's primary water source. Fires in this area pose a serious risk to the water supply and the town, and Stromberg has prioritized the development of the Ashland Forest Resiliency (AFR) Project as a way to mitigate these risks. The AFR Project is a collaboration of the City of Ashland, USFS, the Nature Conservancy, and Lomakatsi Restoration that has implemented a long-term tree thinning and controlled burning program. Every 5-7 years, thinned areas are revisited and burned to maintain low fuel loads. This project has become a national example and is projected to scale up into the Rogue Basin Strategy. Many lessons were learned and negotiations took place during the AFR Project development, Stromberg explained. Balancing the health risks of smoke from prescribed burning against the risk of wildfires themselves is a conversation that is very challenging.

Initially, Oregon state policies did not provide the flexibility needed to conduct the prescribed burns required to keep fuel loads low. To address this, the State of Oregon Smoke Rules Review Committee developed new rules. Now, there is a 3-year process of negotiating with the Oregon Department of Forestry, the Environmental Quality Commission, and the Oregon Health Authority, who are all involved in the regulatory structure by which the EPA air quality standards are enforced in Oregon. Exemptions are available for communities that have adequate "community smoke mitigation programs" to compensate for the potential smoke exposure resulting from prescribed burning. The Smokewise Ashland program serves as this program for Ashland, allowing the AFR Project to conduct burns. Stromberg said that these new rules are better but still do not allow for the extent of prescribed burning necessary to keep up with new fuel accumulation. Stromberg also noted that when areas are thinned initially, the

BOX 3. Suppression Changes Forests and Future Fire Behavior

Skelly provided a simplified example of the effects of fire suppression within a ponderosa pine forest. Historically (top image), fires would move through this ecosystem type about every 3-12 years, depending on where in the United States the forest is located. Grasses and some branches and woody debris would accumulate in the understory between fires but in relatively small quantities. Fires would remove lower branches (i.e., ladder fuel) on the trees, leaving smooth trunks and a relatively open understory. Frequent fires also resulted in a diversity of tree age classes and tree spacing across the landscape.

With 100+ years of fire suppression (bottom image), the ponderosa pine ecosystem has persisted but looks quite different and behaves differently when it burns. Some trees without lower branches because of previous fires are still present, but there are also many more trees that have grown in. There is also a large amount of understory material which acts as ladder fuel and can move fire from the ground into the forest canopy. This results in a more intense and severe wildland fire than would have occurred with the historical, more frequent, fire frequency.

SOURCE: Skelly presentation, artwork by John D. Dawson (https://www.jdawsonillustration.com).

biomass that is removed also needs to be addressed—burning it can create very smoky conditions. There are new high-temperature-combustion techniques that may be appropriate to consider as this and other projects scale up.

A State Government Approach

Michael Benjamin, California Air Resources Board (CARB), explained how the state air quality agency is striving to balance the need for more prescribed fire on the landscape with public health concerns related to smoke exposure. Prescribed burning is a key tool in combating wildland fires and is increasingly being used in California. In 2020, the state, in agreement with USFS, set a goal of treating 1 million acres of forest and wildland each year, including the use of prescribed burns. Conducting prescribed burns in California involves many partners working together to accomplish all necessary tasks, from identifying safe conditions to conducting the burn itself (Figure 6). Public support is also a critical element in prescribed burning, and Benjamin explained that through a focus on outreach, the public is beginning to understand the need for prescribed burning and the trade-offs between some smoke during times when favorable conditions can be chosen compared to out-of-control wildland fires that can result in some of the worst air quality ever seen in the state.

CARB participates in prescribed burning in a variety of other ways. The agency determines where and when prescribed burns can be conducted, based on meteorological considerations designed to protect public health and air quality. The agency is also responsible for tracking prescribed burning activities through the Prescribed Fire Incident Reporting System. This online database allows for streamlined permitting and approval for prescribed burns for land managers and helps CARB to track progress in meeting prescribed fire goals. There is also research within the agency focused on determining whether there are a sufficient number of "ok to burn" days in a year to achieve prescribed burn goals, since unfavorable conditions and times of active wildland fires often need to be avoided. The number of burn days can also be reduced if there is insufficient personnel on the ground to conduct the burns when conditions are favorable. Preliminary results suggest that there are a reasonable number of days available for burning in the Sacramento area based on fuel moisture information, and there are plans to expand analysis to the entire state and for longer time periods, Benjamin said.

Benjamin noted that it is critical to identify specific roadblocks, friction points, or resource limitations to managing forests to mitigate fire risks. Addressing these challenges involves working with partners across government, the private sector, academia, and the public. These outreach efforts will help strike the balance between meeting public health air quality concerns and managing forests to lessen the occurrence of catastrophic wildland fire events.

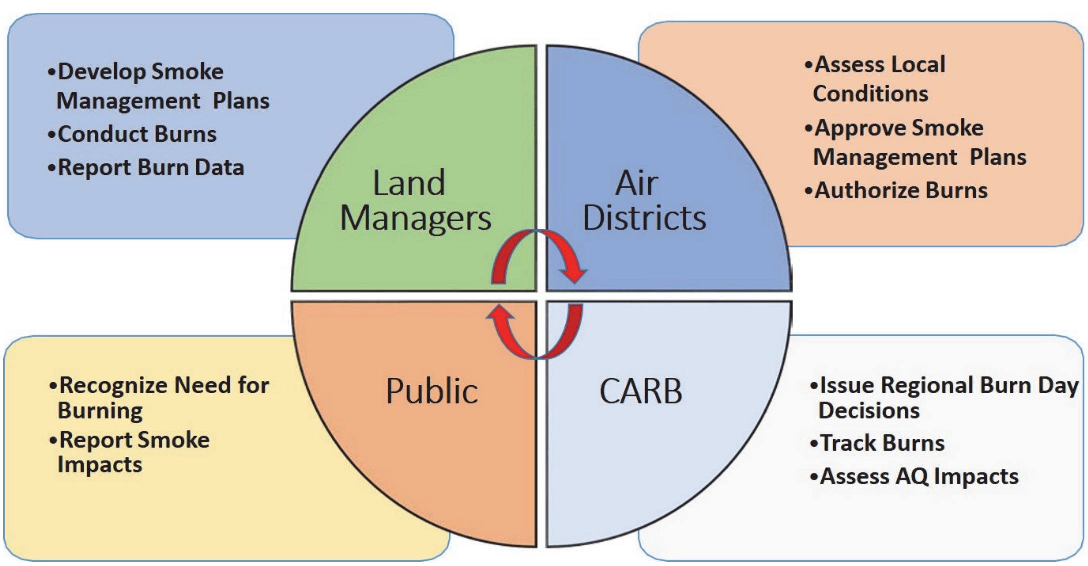

FIGURE 6. Partners engaged in prescribed burning in California and their respective responsibilities. SOURCE: Benjamin presentation.

Occupational Protections for Outdoor Workers

Lee Newman, Colorado School of Public Health and School of Medicine, explained the health risks to those who work outside and are exposed to wildfire smoke, often in combination with other stressors. A broad range of worker types are exposed to wildfire smoke, Newman explained. For example, in Guatemala, workers in sugarcane fields conduct physically demanding work while concurrently being exposed to $PM_{2.5}$ at levels of about 300+ $\mu g/m^3$ during an 8-hour shift. Exposure to high degrees of heat and humidity, air toxins, and strenuous activity in the context of smoke have the compounding effects of high respiratory rate and dehydration, which contribute to the health impacts. A growth in the occurrence of kidney disease has also been observed, including in young workers.

To protect individuals and communities more broadly, new strategies to mitigate exposure and protect outdoor workers are needed, Newman said. Wearing an N95 respirator is insufficient for the conditions workers are often in. Respirators are uncomfortable and will saturate with moisture and become less effective when workers sweat. Unhealthy working conditions not only impact the individuals exposed but also affect their productivity and ultimately contribute to a loss of access to commodities or food insecurity when agricultural workers are impacted. What hurts workers hurts everyone—including families and communities locally and globally, Newman said.

Occupational Protections for Firefighters

Olorunfemi Adetona, The Ohio State University, provided an overview of occupational health concerns for wildland firefighters. Potential exposure of wildland firefighters (Figure 7) is increasing as a result of larger wildland fires, the use of prescribed burns, and the size of the U.S. population living in fire-prone areas. The exposure of firefighters working at the fire line is very complex due to how much time they spend in the plume (determined by specific tasks), the type of vegetation burning, and the many other sources of air pollutants present (e.g., suspended dust, emissions from tools that are combusting petroleum fuels, emissions from burning structures). PM is the measure that has traditionally been used for exposure assessments for this group; however, the relationship between PM and other toxics in wildfire smoke may vary across fires, and it is unclear whether PM is the best measure to use for all health outcomes. Alternative measures that have been used include CO as well as urinary biomarkers such as metabolites, PAHs, and methoxyphenols. There are limitations with these measures. For instance, CO may underestimate exposure, and biomarkers are not necessarily specific to wildland fire smoke.

Most of what is known about adverse health effects of smoke exposure for firefighters relates to acute physiological responses. These include oxidative stress, inflammation, and decline in lung function. There is limited information on the chronic effects of repeated exposure, but effects are expected given what is known from studies of other combustion sources. The few studies available for wildland fire reported an association between career

FIGURE 7. Image of wildland firefighters in the field. SOURCE: Chieh-Ming Wu, in Adetona presentation.

length and increased rates of hypertension (Semmens et al., 2016), an increase in lipid markers across a fire season (Coker et al., 2019), and estimated increased risk of lung cancer and cardiovascular disease (Navarro et al., 2019). To protect firefighters from these health outcomes, greater exposure control and exposure pathway research is needed, Adetona said. Currently, there is no commercially available respirator that meets necessary requirements for flame resistance, clean air delivery over extended periods of time, and portability. For now, stopgap measures could be put in place to reduce inhalation exposure, but Adetona suggested that research should also focus on improved understanding and safeguards to reduce "total exposure" and exposure through other routes, such as through the skin.

Avenues to Improve Human Health Protections

Speakers discussed information needed to protect health for the next few decades. In the near term, access to reliable, real-time information that can be used by the public to make informed decisions and take action to help mitigate exposure to air pollution was suggested. This includes using low-cost monitoring networks, which have expanded in size. Longer-term, proactive management of fire-prone ecosystems to reduce fuel loads is also necessary, several panelists said. Thinning and prescribed burning will not eliminate the possibility of large fires, but strategically placed treatments should lessen the occurrence of catastrophic events and could help to protect key areas and resources like water supplies. Speakers suggested that management will need to be sustained, and in states like California, it will take decades to sufficiently reduce fuel loads.

For the health effects discussed during the session, $PM_{2.5}$ was the central focus, but there are many other pollutants and synergistic effects to consider. For instance, there are interactive effects between PM and O_3 whereby individuals may be more susceptible to the effects of PM when O_3 levels are high. Forecasting this occurrence can be challenging though, because these pollutants do not always co-occur. The interacting effects of substances are also not well studied. For example, per- and polyfluoroalkyl substances are a suite of chemicals often used in the pink foam used as a flame suppressant and have been linked to chronic kidney disease and cancer. Panelists reinforced that there is still much to learn about the constituents in smoke and their variability and co-occurrence. At the same time, exposures are always a mixture of pollutants, so disentangling which constituents are the drivers of health effects is difficult. Even $PM_{2.5}$ is a complex mix of substances.

The AQI was also discussed by the panelists. The AQI is viewed as a useful communication tool because it is simple and understandable to the public (see Box 2). It serves as shorthand way to say “wear a mask” or “do not exercise outdoors above a given AQI,” which is a positive start to reducing exposure. With this simplicity, though, comes a lack of detail from which vulnerable populations in particular would benefit. Some speakers suggested that guidelines should be tailored to different groups, such as those with no respiratory disease, those with cardiovascular disease, and children. Occupational outdoor workers could also have guidelines that account for working outside and exerting themselves while being exposed to air pollutants, and firefighters could have access to personal monitoring equipment to track the quality of air they are inhaling. Another challenge of the AQI is that the information can be misused. For instance, some may interpret that an AQI of 149 does not require a respirator while an AQI of 150 does, despite the air quality being quite similarly poor for both values. Additionally, the AQI is developed based on a relatively sparse network of monitoring sites, meaning that individuals are making decisions based on data that may not be representative of their exact location.

Environmental justice came up in many discussions in this session. For the occupational workers who cannot stay indoors during poor air quality conditions, there is usually little choice other than to work under the conditions or risk losing their jobs. These workers may also suffer from other health conditions or have limited access to health care. Questions of justice also arise when considering prescribed burns, especially for firefighters, who will have increased exposure with more planned burn events. Without measures in place to better mitigate exposure, speakers noted that firefighters are at greater risk of health effects.

Respiratory Viral Infections and Wildfire Smoke

Sarah Henderson, British Columbia Centre for Disease Control, spoke about links between the health effects of wildland fire smoke and respiratory viral infections, including COVID-19. One of the features of smoke that makes it so troublesome from a health standpoint is that the individual particles are very fine. Within the classification of $PM_{2.5}$, many of the particles are less than 1 micron (PM_1) and are an agglomeration of even smaller particles. These agglomerations consist of particles with a large surface-area-to-volume ratio, which increases their interactions with cells encountered in the respiratory tract and lungs. Smaller particles can also penetrate more deeply into the lungs.

Some health effects of concern relate to the body's direct response to a virus when smoke is present. When a person contracts a respiratory virus, the body's immune response is to produce macrophages that consume and remove the virus. If smoke particles are present, the body must fight both the smoke and the virus at the same time, reducing the effectiveness of the response. An additional challenge from smoke when compared to a virus is that the body cannot neutralize the particles, which results in secondary effects of inflammation, spillover into the bloodstream, and impacts on other parts of the body. Smoke also impairs or clogs up the small hairs in the respiratory system (epithelial cilia), meaning that virus may stay in the respiratory tract whereas in the absence of smoke it would be cleared. This provides more opportunity for a viral infection to establish when smoke is present. The evidence presently shows that respiratory and cardiovascular health effects are strong for both wildland fire smoke and COVID-19 infections and that the interactions between these acute effects will be important to investigate further. Longer-term immunosuppression from exposure to wildland fire smoke is also a concern, Henderson noted.

Currently, there is limited information about the interactions between wildfire smoke and respiratory viruses, and even less about smoke and COVID-19. Research that is available has shown that PM from biomass burning has a considerable impact on the occurrence of influenza infections (Croft et al., 2020) as well as a relationship between exposure to air pollution ($PM_{2.5}$, PM_{10}, CO, NO_2) and higher likelihood of being infected with COVID-19 (Zhu et al., 2020). Work by Henderson (2020) modeling the relationship between smoke and the COVID-19 epidemic curve suggests that a fire event occurring during a time of high COVID-19 infection rate could increase the estimated number of cases and deaths by 10%. This is because those exposed to smoke and COVID-19 concurrently are more likely to develop an infection and spread it to others, and may also develop a more severe infection themselves. It is also possible that a response may be delayed, for instance, resulting in a higher than expected infection rate during the influenza season occurring months after an extreme fire season (Landguth et al., 2020).

Planning for the public health impacts of the co-occurrence of wildfire smoke and COVID-19, influenza, or future pandemics is needed, Henderson said. Addressing changes needed over the long term such as building codes is important, but in the shorter term, preseason preparedness for the fire season is key to midseason successes. Guidance for how individuals should shelter in place, long-term care facilities, acute care facilities, schools, and daycares, all with COVID-19 considerations included, would likely be useful. Within the research community, Henderson suggested that it is critical to consider health outcomes of wildland fire smoke and COVID-19 in smoke-impacted places to determine what these relationships are; it will remain unclear how important smoke is in affecting COVID-19 until the research is conducted.

Some Session Themes

Christine Wiedinmyer, CIRES, provided a summary of the second session. Some key themes she identified across the session included the following:

- Climate, weather, fire, emissions, air quality, and health are all connected. Understanding these areas independently as well as their interconnections is important for protecting human health.
- A lot is known, but there is also a lot to learn. The tools are not perfect, but steps can still be taken now to protect health as the science continues to advance and improve understanding.
- When vegetation is present, burning will occur. It is just a question of when, how often, and how severe wildland fires will be. Better understanding of these factors will help communities adapt and mitigate effects.
- Funding and mechanisms that foster cross-disciplinary and long-term health effects studies, facilitate collection of additional emissions and chemistry data, and support communications and outreach efforts can all contribute to protecting public health.

How Do We Get There?

The final session of the workshop took a more aspirational view, looking to opportunities as well as available and emerging approaches and tools to improve wildland fire science and communication in the coming years.

Managing California's Forests for the Future

Mary Nichols, chair of CARB,[1] provided an overview of the causes of wildfire in California and how to manage forests to mitigate future risk. The increasing size and severity of fires in California has resulted in millions of people in urban and rural areas being exposed to smoke for extended periods of time. Of the 20 largest wildfires on record since 1932, 17 occurred in the past 20 years, with 5 occurring in 2020 alone, and the fire season was not yet over at the time of this workshop. Acreage burned by wildfires across this state has more than doubled in the past 30 years, with almost 3.5 million acres burned so far in 2020. These observations reflect a feedback loop involving climate change, forest health, and wildfire (Figure 8). Nichols noted that reducing this feedback loop is important to lowering fire risk, promoting community safety, improving water quality and supply, improving air quality and human health, and sequestering carbon.

There is room for optimism, Nichols said. Increased partnerships and relationships are forming among air quality agencies, land managers, and public health officials, and there is greater appreciation of the health impacts of wildfire smoke. There is a shift away from the concept that suppression is the answer for preventing fires and new focus on a more holistic forest management approach, including much more extensive use of prescribed burning. There is also a growing public recognition and acceptance that some smoke from controlled prescribed fire can reduce overall smoke impacts and is preferable to uncontrolled catastrophic wildfires and associated smoke episodes.

Nichols shared that restoring forests to a more healthy state requires much more prescribed burning, along with physical thinning. Over the past year, prescribed fire treatment in California has doubled to roughly 200,000 acres as the state moves toward a goal of treating 1 million acres annually with prescribed fires. This is expected to reduce the likelihood of large fires and promote other aspects of forest health, including carbon sequestration, biodiversity, healthy watersheds, and more stable economies. Nichols explained that there is a need to evaluate existing and new policies, plans, and programs to identify how to incorporate carbon stored in forests. This can maximize the limited funds available to take advantage of synergies that address multiple objectives at the same time. California is now approaching forest management, fire mitigation, air quality, and climate strategies through a holistic lens that spans all sectors of the economy. The recent large fires have expedited efforts toward goals to reach zero emissions for some vehicles in the coming decades to help to mitigate climate change. Recognizing that climate ties sectors together, the California Climate Investments Program was launched in 2014 and is a statewide initiative that pulls billions of cap-and-trade

[1] Mary Nichols' term as chair of CARB ended in December 2020.

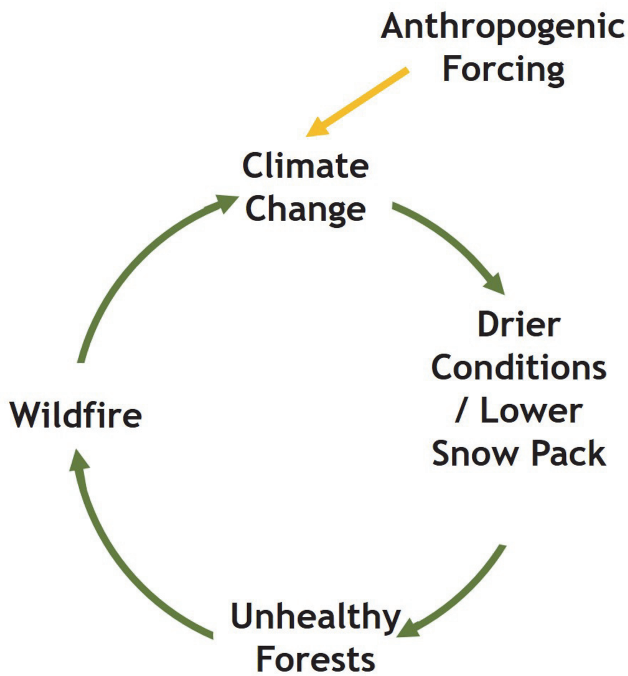

FIGURE 8. Human-driven (anthropogenic) climate change has led to extended droughts and reduced snow pack in California, which has stressed forests. Fire suppression activities over the past century have also led to a buildup of fuels well beyond what would be common in presuppression times. Stressed and unhealthy forests are also more susceptible to disease, and recent bark beetle infestations have left more than 147 million dead and dying trees in California that can act as a fuel source. These conditions make forests more susceptible to catastrophic wildfires, which in turn release greenhouse gases and contribute to further climate change, thereby reinforcing the cycle. SOURCE: Nichols presentation.

dollars from auctioning of allowances to work toward reducing greenhouse gas emissions. Through this mechanism, cap-and-trade dollars are being used by the California Department of Forestry and Fire Protection as well as other land managers to conduct prescribed burning and other wildfire risk reduction and forest restoration activities.

Looking ahead, devastating wildfires will continue until forests reach a more healthy condition, Nichols said. It will take years and potentially decades of focused collective action at the state, local, and federal levels to address this challenge. She added that it will require working together to deliver a clear and unified message to the public about the role of prescribed fire in maintaining a healthy, natural landscape. Continued development and improvement to reach the most effective and holistic approaches to mitigating wildfires may be warranted, recognizing the role that land use and other planning decisions play in addressing these risks. Collective efforts aimed at securing resources sufficient to implement identified actions and a firm and confident commitment that fosters and strengthens all kinds of relationships around these topics can make this possible.

Obtaining the Information Needed for the Coming Years

This workshop panel explored opportunities to improve the production and exchange of information about air quality and health effects between atmospheric and health communities and more broadly, with a focus on needs over the next 5 to 10 years and capabilities for research and mitigation of health impacts.

Toward Better Understanding of Smoke Health Impacts from an Epidemiological Perspective

Sheryl Magzamen, Colorado State University, spoke about the health effects of wildland fires and what the future holds from an epidemiological perspective. In her remarks, Magzamen highlighted four key areas that have arisen in her research.

First, studies that evaluate the long-term health effects of chronic, repeated exposure to wildfire smoke within cohorts over time are lacking. This includes both the long-term effects of acute exposures and impacts of chronic, repeated exposures to wildfire smoke. New research suggests that lung function can be impaired a year after smoke exposure (Orr et al., 2020) or make individuals more susceptible to respiratory infections after the fire season, as discussed previously by Henderson. However, most studies to date have been retrospective analyses that looked at acute seasonal or multiseasonal events leveraging secondary health data combined with atmospheric chemistry data to assess exposure and match exposure to health outcomes. Magzamen said that currently wildfires are treated like episodic natural disasters in epidemiological studies but instead should be treated more like a chronic pollutant.

Second, Magzamen noted that research is needed to differentiate the health effects of $PM_{2.5}$ from different sources. Information about household air pollution and experimental studies show that biomass burning may result in different particle composition and toxicology due to the type of fuel, the burn intensity, and the transport and mixing of those pollutants. Research focused on the long term, as well as “critical windows” where individuals may be more susceptible to negative outcomes (e.g., exposure during pregnancy), is particularly lacking.

Third, there is limited understanding of how communication about wildfire smoke influences behaviors to avoid or mitigate smoke exposure, especially as it relates to vulnerable populations. Magzamen discussed a case study for Colorado which showed that during local fires in 2012 there was a decrease in hospitalizations and emergency department visits associated with asthma. However, in 2015 when the state experienced smoke that was transported from much farther away, increased health care utilization was observed, suggesting possible differences in decisions to avoid or mitigate exposure based on proximity to the fire and associated emergency response.

Finally, Magzamen reinforced the message that there is a need to manage lands in order to reduce health effects from wildland fires. There is currently a lack of integration of information about health impacts in downwind communities during prescribed burns, and improved understanding of both short- and long-term impacts of this type of management is needed, Magzamen said.

Improving Firefighter Protection from Smoke and Other Respirable Particles

Tim Reinhardt, Wood Environment & Infrastructure Solutions, spoke about priority areas to reduce hazards for wildland firefighters. Firefighters are exposed to smoke as well as dust produced when soils are disturbed. CO measured in smoke at the fire line strongly correlates with exposure to other toxic substances, such as formaldehyde, and can therefore provide a good representation of exposure levels if monitored in real time. Reinhardt noted that measurement of PM_1, and in particular the organic carbon fraction of PM_1, is needed for considering long-term adverse health effects. At the same time, dust can contain respirable crystalline silica which has low exposure limits in the occupational setting, and these limits are routinely exceeded without respiratory protection when firefighting. The permissible exposure limit for respirable dust enforced by OSHA and state agencies has been applied in the context of wildland fire smoke. Given what is known about the toxicity and carcinogenic potential of smoke, this limit is unacceptable, Reinhardt explained. More research is needed to better understand acceptable exposure limits to various toxins (e.g., cellulose, respirable crystalline silica, hexavalent chromium, beryllium) in this occupational setting, and, in the meantime, new lower limits should be established as steps are taken to introduce various controls, Reinhardt said.

There are controls that have been put in place for both engineering (e.g., enclosed-cab dozers) and administrative (e.g., prescribed burn planning improvements) aspects of firefighting, but they have not been demonstrated to be effective in mitigating exposure. Looking to the future, increased prescribed burning and a large incentive to control prescribed fires will increase firefighters' exposure, which heightens the importance of addressing exposure issues. Respirators will probably be the main tool that is used, Reinhardt said, but no respirators are currently approved for use in this context. The National Fire Protection Association arrived at a respirator standard in 2016. The minimum respirator to be worn is a half-face N95 respirator with ultralow breathing resistance; ember resistance; and removal of CO, formaldehyde, acrolein, and other organics and acid gases. Half-face masks do not help eye irritation issues, but they do not fog up in hot conditions. There are also remaining challenges with N95 masks because they are unable to control for silica and other smoke toxins concurrently. A full-face powered air-purifying respirator made to the 2016 standard would be a useful tool, Reinhardt explained. However, these respirators are costly, there are currently no manufacturers, there is not a guaranteed market, and they have the potential to hinder communication and could lead to loss of situational awareness with fatal outcomes.

Factors for Improving Air Quality

Dan Jaffe, University of Washington, discussed four key factors where better understanding is needed to improve air quality and inform both policy and public health questions: O_3, unique smoke markers, prescribed versus wildland fire smoke, and indoor air quality. First, it is well known that smoke contributes to O_3 production and O_3 exceedances in urban areas, but as discussed by other speakers, there is poor understanding of O_3 processes, such as changes caused by individual smoke plumes mixing with urban air and plume movement downwind that causes O_3 exceedances far from the source. Smoke can sometimes travel thousands of miles from the source and may remain aloft or move downward to reach the surface. Whether the smoke reaches the surface becomes an important policy and health question because it is the surface smoke that most directly affects the air people breathe. Regulatory monitoring sites that measure PM cannot distinguish between smoke and other PM sources without unique smoke markers. Better tools for routine monitoring to identify and analyze smoke, especially at low to moderate concentrations, are needed, Jaffe said.

Like other workshop speakers, Jaffe noted that PM emitted from prescribed fires can be dramatically less than that of wildland fires when comparably sized areas have burned. For example, comparing wildland fires in California to prescribed fires in Texas in 2017, Jaffe et al. (2020) found almost an order of magnitude greater quantity of $PM_{2.5}$ emissions from the wildland fires than from the prescribed burns during the peak month of fire (Table 1). Jaffe remarked that the amount of biomass consumed per acre by wildland fires is greater and contributes to this observation. However, the similarly large difference between values for the highest measured daily $PM_{2.5}$ quantity during the peak month reflects large differences being captured at the surface across monitoring sites within each state. This suggests that smoke exposure may have been lower in Texas in 2017 and demonstrates that prescribed burns are an important tool for managing smoke and associated air quality.

Last, Jaffe explained impacts of smoke on indoor air quality and ways to mitigate smoke in homes. During recent smoke events, common guidance has been to stay indoors with the windows closed. However, there is very little information available about changes to the indoor environment during smoke events on which to base this guidance. There is a little evidence to indicate that indoor concentrations of fine PM can be nearly as high as outdoors, and Jaffe suggested that a comprehensive overview is needed that considers PM size distribution, O_3, CO_2, and other pollutants. To address indoor air quality concerns, there are relatively simple and low-cost tools to reduce exposure. For instance, anecdotal evidence suggests that using a low-cost box fan and MERV-13 filter combination can keep a home to a PM concentration that is about 20% of that experienced outdoors, while homes without any type of ventilation system reached concentrations at or near that of the outdoor air.

Using Models to Estimate Smoke Exposure

Yang Liu, Emory University, discussed exposure modeling used to support health effects research. Traditionally, air quality is measured from ground monitors, located largely in cities that are part of the regulatory monitoring network. Because wildland fires often are located far from city centers and it is known that smoke chemistry and dispersion change during smoke transport, there is a disconnect between the data that are available and the data that are needed. Chemical transport models are an important tool in studying health effects but often cannot estimate spatiotemporal smoke patterns because of imperfect emission estimates, complex terrain, coarse resolution, and limited knowledge of the chemistry.

Liu and colleagues have compared and incorporated information from chemical transport models with ground-based and satellite observations to improve estimates of daily $PM_{2.5}$ concentrations (Geng et al., 2018). Running the Community Multiscale Air Quality (CMAQ) Modeling System with full coverage in space and time at a 12-km resolution yielded a poor correlation between modeled values and ground observations. However, when satellite data and a Bayesian statistical modeling framework were incorporated, the relationship

TABLE 1. Area Burned and Associated $PM_{2.5}$ Emitted from Wildland Fires in California and Prescribed Fires in Texas in 2017

State	2017 Area Burned (ha)	Peak Month	Peak Month-Area Burned (ha)	Peak Month-$PM_{2.5}$ Emitted (tons)	Highest Daily $PM_{2.5}$ in That Month (μg/m^3)
Wildfires:					
California	641,440	October	151,492	106,657	215
Prescribed Fires:					
Texas	632,470	February	143, 468	12,807	29

SOURCE: Table and data from Jaffe presentation and EPA National Emission Inventory for 2017. Modified from Jaffe et al., 2020.

improved considerably. Building on obtained results, Liu and colleagues built a spatial calibration model to improve the CMAQ correlation and a Bayesian ensemble model, to combine the calibrated CMAQ and satellite-estimated $PM_{2.5}$ data. They were able to produce a 1-km-resolution product showing daily $PM_{2.5}$ concentrations that tracks high-PM regions quite well, Liu said, but there is room for continued improvement in model performance. A remaining challenge with utilizing satellite data for these analyses is that they are only available for about 50% of the time, when it is not cloudy.

Models can also be used to evaluate the role of the smoke source in health outcomes. Running CMAQ with and without smoke emissions in combination with satellite data on total $PM_{2.5}$ can help to isolate smoke $PM_{2.5}$ from other sources, but this is very computationally expensive. Modeling research by Liu and colleagues suggests that looking just at ambient measurements of $PM_{2.5}$ could lead to misclassification of the source of $PM_{2.5}$ exposure depending on where individuals are located. Being able to isolate the source can affect health outcomes, as one study showed increased asthma risks in children and adults when wildfire smoke concentrations were higher (Stowell et al., 2019). Liu presented one possible interpretation: Fire smoke may be more toxic than ambient $PM_{2.5}$.

Supplemental data to improve modeling efforts can come from crowdsourced, low-cost sensors. Liu found that in California, PurpleAir sensors provide 10 times the hourly $PM_{2.5}$ concentration measurements of the EPA network, although uncoordinated locations means that individual sensors are not as spatially representative as those in the EPA network (for which sites are carefully selected). PurpleAir sensor calibration is also needed to address systemic biases, Liu noted. A machine learning model trained with EPA monitoring data and weighted sensor data showed higher annual average PM concentrations throughout most of California than the EPA data alone, suggesting an underestimate of regional population exposure when using only EPA measurements. Particularly high PM concentrations occurred in "hot spots" that corresponded to large wildland fires (Figure 9). The synergistic application of new and emerging technologies and tools with chemical transport models would greatly benefit air quality management and fire smoke health effects research, Liu stated.

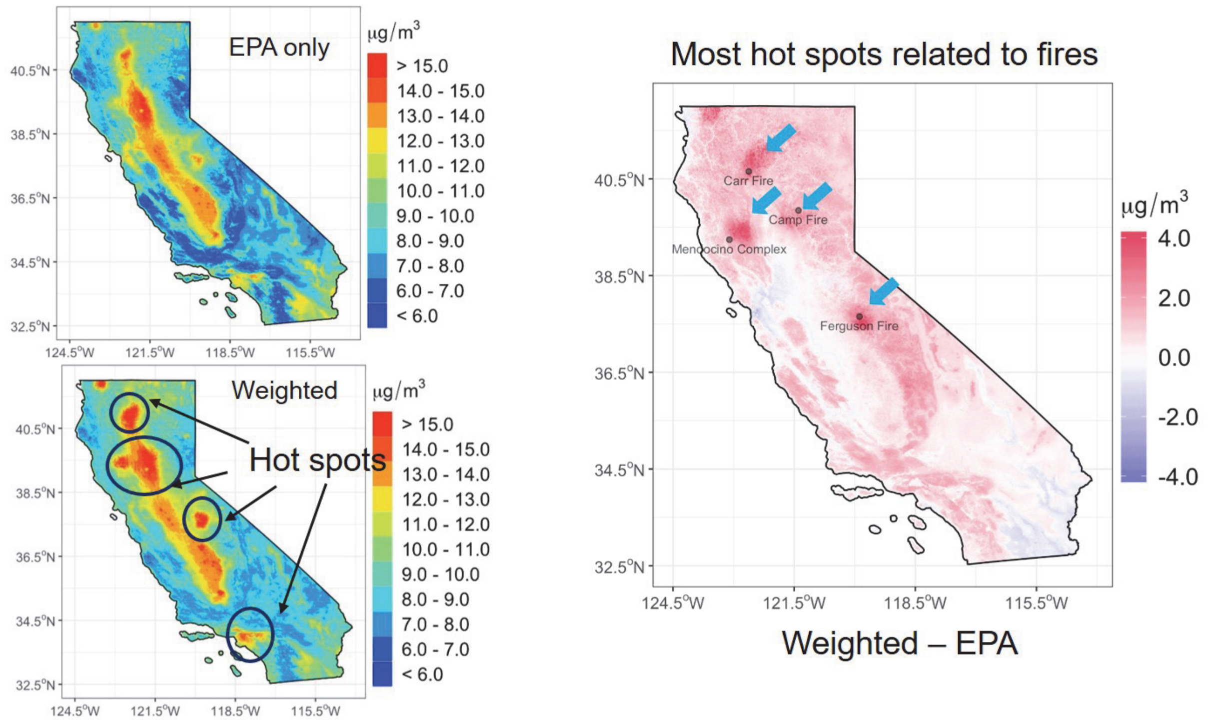

FIGURE 9. Modeled estimates of annual average PM concentrations in California including data from EPA monitoring sites only (top left), weighted values including additional available sensor data (bottom left), and data sources combined (right). Particularly high PM concentrations occurred in "hot spots" that corresponded to large wildland fires (labeled with blue arrows on right panel). SOURCE: Bi et al. (2020), in Liu presentation.

Improving Understanding through More Data and Preparation

Speakers discussed the need for expanded data collections and long-term data sets that allow for the study of effects across multiple fire seasons. When it comes to data collection and data assimilation systems, there is value in expanding the availability of collected data and assimilating data records where possible to increase use in long-term studies and for utilization in modeling. The importance of broader monitoring networks that can be used to validate satellite and modeling information was also emphasized. Expanding the number of air pollutants routinely monitored beyond O_3 and PM over larger networks could also provide new insights into attribution of sources and understanding of exceedances.

Looking to the future, several speakers stressed the need to prepare—the wildland fire problem is not going away. Preparing communities and health agencies with the right information and tools is one key mechanism to reduce exposure and build resiliency. Preparation includes improved communications both for response to acute fire events when conditions may be very smoky as well as to increase awareness of poor air quality farther downwind where populations may not realize they are being exposed. New standards that address occupational exposure may also be useful to protect those working outdoors and on the front lines.

Improving Information Exchange for the Future

The final panel of the workshop addressed how to improve the ways wildland fire and health effects information is communicated to public audiences.

Partnerships to Advance Communications of Fire Risk

Pete Lahm, USFS, explained efforts to improve information exchange to reduce risks from fire and smoke undertaken by the Interagency Wildland Fire Air Quality Response Program (IWFAQRP) and other partnerships. The IWFAQRP works to improve daily communications about changes in fires and risks around smoke to try to modify human behaviors that lead to reduced smoke exposure. These efforts are coordinated among various federal, state, and local agencies, tribes, and other groups. This coordination involves utilization of monitoring data, smoke dispersion modeling, satellite products, and web tools, and integrates information from incident management teams on the ground supporting wildfire response. Air resource advisors plan the communication efforts and work as part of the IWFAQRP but are deployed with the incident management teams. These advisors consider all available information to determine what needs to be shared with the public. It is a difficult job to translate fire information into anticipated smoke exposure in a downwind community, Lahm said. Examples of immediate information needs could be determining what will burn tomorrow and what will burn 3 days from now, or identifying a canyon region where fire is likely to start or expand rapidly soon. Lahm emphasized the importance of partnership in the IWFAQRP efforts, noting that the only way to continue to improve information exchange is going to be to operate as partners and ensure that all the right agencies participate. In 2019, the IWFAQRP was recognized in congressional legislation as an important component in addressing risks of wildland fires, and the program continues to improve as more lessons are learned each fire season. Another recent partnership Lahm explained is a pilot study between EPA and USFS to pull together low-cost air quality sensor data to augment the permanent $PM_{2.5}$ monitoring data network.

An advantage of IWFAQRP is that it works as both an operational and research framework in that it allows for real-time data evaluation as part of the toolboxes provided to air resource advisors. Lahm showed how the AQI changed across the state of Oregon between mid-August and mid-September 2020 (Figure 10). The gray shading across the top of the graphic reflects the fraction of the population that does not live within 50 km of a permanent monitoring site. Low-cost sensors would make it possible to fill in this gap.

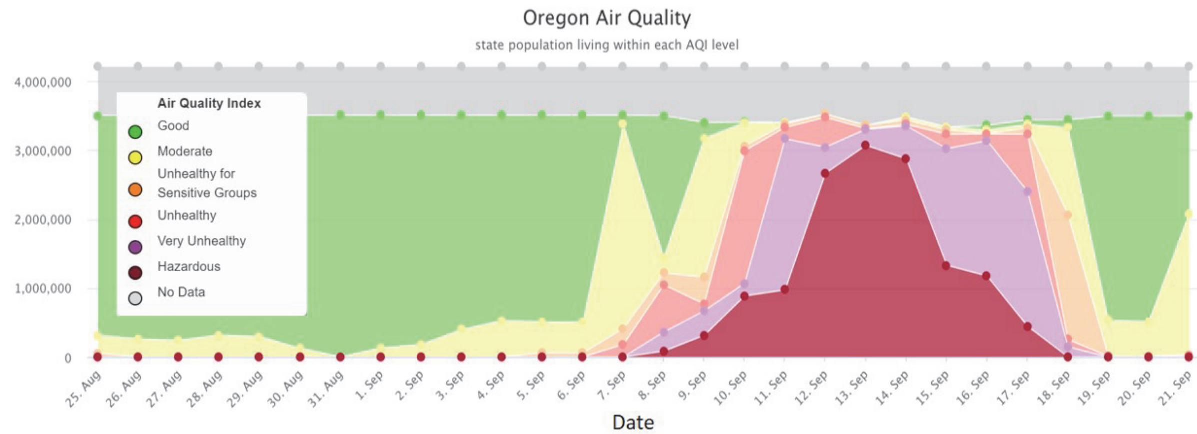

FIGURE 10. Air Quality Index estimates across the state of Oregon for mid-August to mid-September 2020. SOURCE: Lahm presentation.

Lahm stated that protecting the public comes down to awareness and being "smoke ready." Identifying those at risk and ensuring they are prepared to address high smoke conditions involves some key steps:

- determining whether those at risk know they are and, if not, determining how to inform them;
- identifying what information is missing from current information streams;
- considering whether there is a system for smoke preparation; and
- developing a prescription for preparation (i.e., understanding smoke potential from fires, impacts at various scales from local to global, and the possible role of medical insurance in prescribing solutions like air filtration devices).

Communicating with At-Risk Populations

Susan Stone, EPA, discussed steps being taken to improve information exchange with at-risk populations, particularly children, older adults, and those with heart and lung disease. She said that a key way to reach at-risk populations is through health care providers because people are more likely to act when instructed to by their provider. However, research has shown that providers often do not discuss air quality and how it may interact with other conditions (e.g., Mirabelli et al., 2018; Wen et al., 2009). In an effort to fill this void, EPA and CDC have developed a continuing education course based on information in the *Wildfire Smoke Guide for Public Health Officials* report (2019) and associated fact sheets, produced collaboratively by six federal and state agencies. Other organizations are also developing educational materials and resources to help enable those within the medical community.

A potential avenue for getting information about wildland fire risks to vulnerable individuals is through health insurance companies and the electronic medical records system, Stone said. General messaging about preparedness, health effects of smoke, the AQI, and how to reduce exposure and symptoms of concern could be relatively straightforward. Although more challenging, it may also be possible to build on this to develop a smoke action plan template that could be completed by individuals and their providers to create plans that meet individual patient risks and needs. A benefit of this approach would be the ability to evaluate the effectiveness of the plan annually in terms of its ability to reduce smoke exposure and to deal with consequences if one is exposed, and to then update the plan as needed.

Many of the questions EPA receives relate to minimizing smoke exposure for schools, daycares, and camps. At the time of this workshop, expert workgroups were in the process of developing recommendations and planning a 2021 workshop to address these concerns. Key areas being explored include respirator use in children, improvement of indoor air quality in schools, school activity guidelines, and the use of indoor and outdoor air quality sensors. From a practical standpoint, daily air quality forecasts provided to schools in late afternoon and early morning may be most useful, much like information is shared for snow days, so that parents can keep children home rather than having to pick them up early. Daily smoke forecasts are currently generated in the 7:30-8:00 am timeframe, which is too late for schools to make informed decisions for that day. More fine-scale, hourly forecasts could inform decisions about outdoor activities and how indoor spaces may be used by schools or childcare facilities.

Building on Existing Tools

Michael Brauer, University of British Columbia, provided insights on how to enhance information exchange by building on the forecasting and communication tools that are currently available. He noted that forecasts have been able to predict health outcomes for the past decade, but could be made more useful if focus was placed more heavily on improving temporal and spatial specificity rather than on improving accuracy in forecast magnitude or complexity (i.e., incorporating additional pollutants). Brauer noted that it is often how the information is communicated that is critical rather than the advancements in the details. For example, adding zoom and animation features to a forecast tool in western Canada was the change needed to get smoke data into nightly weather forecasts. Integrating smoke forecasts into weather forecast tools could also be beneficial from a communications perspective.

Increasing awareness of smoke could be improved by extending forecasts, which is likely feasible. This includes forecasting out 7 to 10 days as well as extending to season length or longer fire hazard information and smoke forecasts. Retrospective analyses could also be used to develop hazard maps that identify areas where smoke has been a problem in recent years. This could help stakeholders to prepare for outdoor events and facilitate the development of smoke contingency plans so that organizers are not rushing to make decisions when smoke occurs. He shared that hazard maps would also be useful for determining cumulative effects of multiple exposures.

For communicating risks, Brauer suggested that improvements are needed in how available information may be perceived versus actual risks to individuals. For instance, if the AQI value for a given area suggests very poor air quality but it is not smoky at that location, individuals may lose confidence in the metric. This particular situation could result from how the AQI is calculated—as a rolling average which does not capture hour-to-hour changes—rather than the air quality at a specific time. Removing the rolling-average AQI or just using hourly pollutant measurements in the context of a fire might help address this communication concern. Another opportunity to heighten public awareness of poor air quality risks would be for individuals to install low-cost sensors indoors and outdoors. This provides information about the level of protection being offered by going inside, reinforces going indoors as a mitigation action, and could have immediate beneficial health implications (e.g., Yao et al., 2020).

Finally, Brauer emphasized being prepared. This includes having adequate supplies of medications for disease management, which could lessen health impacts of smoke; having extra filters if a filtration system is in use; and planning for what do to if smoke occurs coincident with other hazards, such as extreme heat. Having communication for extreme heat and smoke that is linked in messaging so that it deals with both hazards is important, he said.

Some Strategies for Communicating Science to Nonscientists

Marshall Shepherd, University of Georgia, provided a big-picture overview of what works and what does not when it comes to science communication. For a topic to be picked up by the media he noted that it needs to have a “so what” factor, and the presence of wildland fires, smoke, and implications for society very much meet this criterion.

Shepherd shared nine tips for communicating science to nonscientists (Shepherd, 2016):

1. Know your audience and tailor the message for that audience; one size does not fit all.
2. Be careful not to use jargon. Terms like “bias” and “positive trends” have very different meanings for scientists than for the public or policy makers.
3. Get to the point and deliver the bottom line first. This contrasts with typical research communications where the background is provided first and bottom line last (Figure 11).
4. Use analogies and metaphors.
5. Make three points. Having three takeaways from messages has been shown to be effective. Also consider the “three m’s”: memorable, meaningful, and miniature.
6. Be confident and clear in sharing what you know. You are the expert.
7. Use social media to reach intended audiences. The social media landscape now has many more looking to the internet for their information.
8. Let go of the myth that scientists who choose to use social media are “popularizers.” Social media is an important tool for engaging with public audiences.
9. Relate. When communicating about implications of smoke for public health or other fire dangers, find what in the at-risk communities’ value system relates for that particular audience. This will be different for different audiences.

Shepherd also posed a few questions to get at how the atmospheric sciences may be able to better provide input to advancing wildland fire science. These questions related to providing greater clarity in the connections among climate change, smoke, wildland fire, and associated attribution; the role that artificial intelligence and machine learning could play in advancing smoke forecasts; and what is missing from weather-climate models that would meet smoke forecasting needs (e.g., greater resolution, less parameterization, process, connection to decision support systems). Finally, Shepherd explained new impacts-based forecasting within

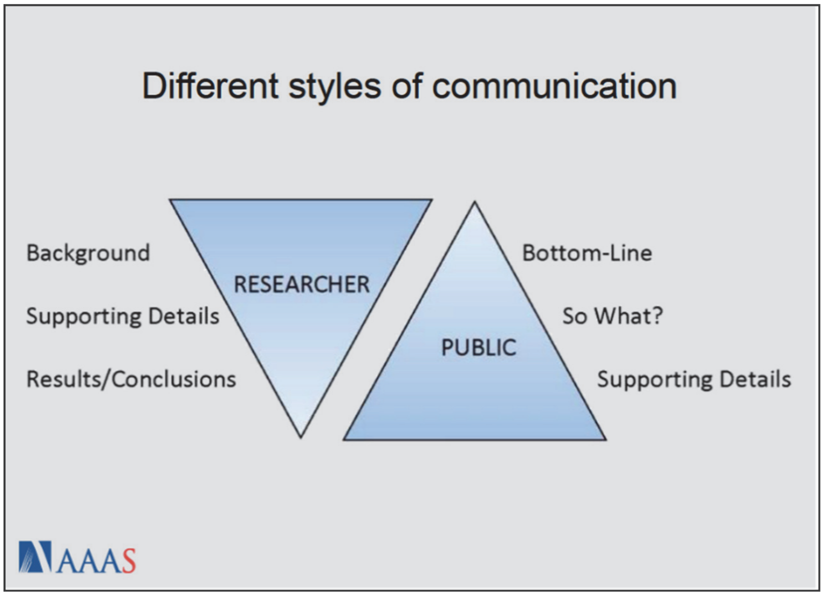

FIGURE 11. Depiction of the contrasting styles of communication between researchers (left) and the public (right). SOURCE: AAAS Center for Public Engagement with Science and Technology (Adapted from Baron, 2010).

the National Weather Service and asked whether there are significant investments being made in the social sciences aspect of messaging in the wildland fire community that could lead to similar messaging approaches.

Improving the Messaging

Panelists discussed opportunities and challenges that come with the emergence of new tools and communication capabilities. For fire and forecast modeling, many models are now available, but they vary in their strengths and what they can provide, meaning that different models may be best suited to meet different needs. As the number of tools and available data sets increases, lessons are being learned about how to communicate the information in ways that resonate with communities, and how to make sure the strengths and limitations of the data are transparent, to lessen the likelihood of information being misused or misinterpreted. Improved coordination around wildland fire activities and communications of risks, including at the federal level, will likely help to get information on fire and smoke out more broadly to the public through channels like news and weather apps.

Additional communications efforts are needed to ensure that wildland fire information reaches those for whom English is not their first language, panelists said. Having trusted communicators within communities who can translate fire information accurately is useful in reaching those who may be at risk. Several panelists also noted a need to increase understanding of how different communities access information. For instance, not everyone has cell phones or internet and may rely on other means like radio to obtain information.

Looking ahead to advancing communications and actions around wildland fire, panelists suggested that additional expert communities could be included in the types of discussions held at this workshop. These communities could include social scientists who can hone ways to message effectively for various audiences, as well as engineers who can provide insights into how to address filtration issues to improve indoor air quality. This meeting was a positive step, but speakers noted that there is still much to be done.

Final Thoughts

To close the workshop, planning committee members reflected on some of the messages they heard during the meeting.

A.R. "Ravi" Ravishankara, Colorado State University, said there is no silver bullet to avoid the problem of wildland fires, but instead they are something to learn to live with. It is very likely the wildland fire problem will get worse as a result of climate change and associated regime shifts, as well as further human encroachment into the wildland-urban interface, he said. Although fires may not be controllable, their societal impact can be reduced through individual actions and efforts to protect communities including vulnerable, underprivileged, and underrepresented groups. Practical steps, such as prescribed burning, provide a way to reduce fires, especially catastrophic ones. At the same time, developing a clear set of research priorities to improve understanding of wildland fires, leveraging new and emerging tools and technologies, and expanding attention on indoor air quality and the influence of multiple stressors on human health could help improve knowledge and reduce risks, Ravishankara noted.

Benjamin built on this, suggesting that community-based engagement to communicate about mitigation options could be an important component of building awareness and reducing risks. Luke Naeher, University of Georgia, noted the value in bridging the exposure health and atmospheric science communities and the unlimited collaboration opportunities among those that participated in this workshop. Anenberg also commented on the opportunities the workshop highlighted related to rapidly evolving science and tools and how these can inform health effects studies and communication.

Narasimhan "Sim" Larkin, USFS, commented on the diversity of impacts discussed during the workshop ranging from the unique susceptibilities of different vulnerable populations to occupations that increase exposure because of outdoor work, to how the construction of one's home can affect indoor air quality. Finding ways to convey information to these different groups in ways that are most valuable will vary; it is not one size fits all, he said.

Warneke noted that workshop presenters explained how extremely difficult and complex the wildland fire problem is, but opportunities to refine understanding of this complexity can come with new data from recent field studies and from new tools that are emerging. At the same time, speakers expressed a desire to have improved air quality forecasts, which will mean trying to simplify what is already known to provide this information. There is also much information already known about smoke that the atmospheric science community could better communicate for use in health effects research and to broader audiences, Warneke said. Wiedinmyer built on this, noting that the specific questions being asked can inform the research approach. For instance, starting from questions that came up repeatedly during the workshop such as "When will smoke arrive?" and "When will it go away?" and using those to shape atmospheric chemistry research directions could provide new ways to make advances in protecting public health.

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Appendix A: Statement of Task

Wildland Fires: Towards Improved Understanding and Forecasting of Air Quality Impacts – A Workshop

Board on Atmospheric Sciences and Climate

Board on Chemical Sciences and Technology

Statement of Task

The National Academies of Sciences, Engineering, and Medicine will appoint a planning committee to organize a workshop on improving understanding and forecasting of air quality impacts from wildland fires. The workshop will convene experts in wildfires, atmospheric chemistry, climate, meteorology, and health together with key decision makers from public health, emergency management, air quality management, and other relevant areas. This includes state and federal stakeholders. Workshop discussions will likely consider the following topics:

- **Characterizing fire activity and their emissions:** How are wildfires expected to change in the next decade in response to climate change and other drivers? Is there sufficient characterization of the effluents from wildland fires, fires at the interface of wildland and urban areas, and prescribed burns and agricultural fires?
- **Atmospheric transport and chemical transformation of fire emissions:** How well understood are the chemical transformations and what is the predictive capability for transport of fire effluents away from fire locations to other parts of the continent? How well understood is the aging of wildfire effluents, including smoke, gas phase constituents that can lead to criteria pollutants, and other toxics? How have the wildfires influenced requests for exemptions from states and what could be expected in the future if tighter air quality standards are implemented?
- **Monitoring and modeling wildfire emissions:** What are the capabilities for real-time monitoring of wildfire effluents from ground level, aircraft, and satellites? Are advances in monitoring technologies (e.g., uninhabited aircraft systems, crowd-sourcing, personal monitors) being taken advantage of? Are the necessary modeling tools available for forecasting impacts on spatial and temporal timescales needed for practical use by the society once a fire has started?
- **Subseasonal-to-seasonal forecasting for fire seasons:** What is the current skill? What capabilities may soon be available? How are decision makers using these products? How could such products be more useful to decision makers?
- **Smoke health impacts:** How well are the health impacts of wildfire smoke understood? What are the primary knowledge gaps? Is the dry $PM_{2.5}$ mass a sufficient indicator of health impacts? How is the knowledge about the impacts and their uncertainties

communicated to those in affected areas (e.g., the public, decision makers (such as schools, hospitals, and housing for the aged), vulnerable populations, etc.)?

- **Communicating wildfire forecasts and mitigation options:** How well do federal agencies, scientists, local and regional managers, public health officials, and other stakeholder groups communicate information about wildfires? How are risks and recommended actions communicated to various populations (affected communities in vicinity of fires, downwind communities, firefighters)? How can weather and other communications expertise be leveraged to improve communication about fire risk?

Appendix B: Planning Committee Biographical Sketches

A.R. "Ravi" Ravishankara (NAS) *(Chair)* is a professor in the Departments of Chemistry and Atmospheric Science at Colorado State University. He was at the National Oceanic and Atmospheric Administration's (NOAA's) Chemical Sciences Division (CSD) of Earth System Research Laboratory for nearly 30 years in Boulder, Colorado. There, he served as the director of CSD from 2006 through 2014 and was a senior scientist before the directorship. Before joining NOAA, he was at the Georgia Institute of Technology in Atlanta. Dr. Ravishankara has worked over the past three and a half decades on the chemistry of Earth's atmosphere related to stratospheric ozone depletion, climate change, and regional air quality. His measurements in the laboratory and the atmosphere have contributed to deciphering the ozone layer depletion, including the ozone hole; to quantifying the role of chemically active species on climate; and to advancing understanding of the formation, removal, and properties of pollutants. He is an author or co-author of more than 350 peer-reviewed publications. Dr. Ravishankara is a member of the U.S. National Academy of Sciences, a Foreign Member of the Royal Society (London), and a Foreign Fellow of the Indian National Science Academy. He is also a fellow of the American Geophysical Union, the Royal Society of Chemistry, the American Association for the Advancement of Science, and the International Union of Pure and Applied Chemistry. His many awards include the Polanyi Medal of the Royal Society of Chemistry, the Stratospheric Ozone Protection award of the U.S. Environmental Protection Agency, and the American Chemical Society's award for Creative Advances in Environmental Sciences. He was a co-chair of the World Meteorological Organization/United Nations Environment Programme (WMO/UNEP) Science Assessment Panel on Stratospheric Ozone and a member of the Science Advisory Panel of the Climate Clean Air Coalition of UNEP. He has served or continues to serve on many national and international committees. He is on the editorial board of the *Proceedings of the National Academy of Sciences* (PNAS). He has previously served as an editor of *Geophysical Research Letters*, and has been on the editorial board of *Chemical Physics Research Letters*, *Physical Chemistry Chemical Physics*, and the *International Journal of Chemical Kinetics*.

Susan Anenberg is an associate professor of environmental and occupational health and of global health at the George Washington University (GW) Milken Institute School of Public Health. She is also the director of the GW Climate and Health Institute. Dr. Anenberg's research focuses on the health implications of air pollution and climate change, from local to global scales. She currently serves on the U.S. Environmental Protection Agency's Science Advisory Board and Clean Air Act Advisory Committee, the World Health Organization's Global Air Pollution and Health Technical Advisory Group, and the National Academies of Sciences, Engineering, and Medicine's Committee to Advise the U.S. Global Change Research Program. She also serves as secretary of the GeoHealth section of the American Geophysical Union. Previously, Dr. Anenberg was a co-founder and partner at environmental health analytics, LLC, the deputy managing director for recommendations at the U.S. Chemical Safety Board, an environmental scientist at the U.S. Environmental Protection Agency, and a senior advisor for clean cookstove initiatives at the U.S. State Department. She received her Ph.D. in environmental science and engineering and environmental policy from the University of North Carolina (UNC) Gillings School of Global Public Health in 2011. She also received an M.S. in environmental science and engineering from UNC in 2008 and a B.A. in biology and environmental sciences from Northwestern University in 2004. Dr. Anenberg was a National Academies Mirzayan Science and Technology Policy Fellow in 2009, working with the Board on Atmospheric Sciences and Climate.

Michael T. Benjamin has more than 35 years of experience in environmental and Earth sciences, with a focus on air quality and air pollution control. He is currently chief of the Air Quality Planning and Science Division at the California Air Resources Board (CARB). In this capacity, he oversees a staff of approximately 170 scientists and engineers who are responsible for a broad range of air quality programs. These include development of State Implementation Plans for California and associated technical work including air quality data analysis, emissions inventory development, and air quality modeling. Other areas under Dr. Benjamin's purview include consumer products regulatory development as well as oversight of California's smoke management program. Since joining CARB in 1993, Dr. Benjamin has served in multiple roles across the agency, most recently as chief of the Monitoring and Laboratory Division where he oversaw California's statewide network of 200 ambient air quality monitors and associated laboratory operations. In his career at CARB, Dr. Benjamin has also served as assistant division chief of the Research Division, overseeing development of the agency's extramural and in-house research programs. Prior to joining CARB, Dr. Benjamin worked for 5 years at Columbia University's Lamont-Doherty Earth Observatory conducting research using chlorofluorocarbons and other tracers to better define the pathways, timescale, and transport for the spreading of deep water from its source.

Narasimhan "Sim" Larkin is a research meteorologist and team leader with the U.S. Forest Service's Pacific Wildland Fire Sciences Laboratory in Seattle, Washington. He also serves as an affiliate associate professor at the University of Washington's School of Forest and Environmental Sciences. At the U.S. Forest Service, Dr. Larkin conducts research in fires, fire emissions, smoke, and air quality with an emphasis on building scientific models and tools to aid in land, fire, and air quality management. Tools and systems built by Dr. Larkin are in use daily across the United States, Canada, and in other countries for air quality smoke impact monitoring and smoke forecasting. These include the BlueSky smoke modeling framework and the BlueSky Playground interactive emissions and smoke modeling web tool. Dr. Larkin is the senior scientific advisor to the federal Interagency Wildland Fire Air Quality Response Program led by the U.S. Forest Service. His work also forms the basis of the wildland fire component of the U.S. Environmental Protection Agency's National Emissions Inventory. He is a co-lead on the large multiagency fire field campaign, the Fire and Smoke Modeling Evaluation Experiment. He received his Ph.D. from the University of Washington studying the El Niño–Southern Oscillation climate pattern.

Luke P. Naeher is a professor in the University of Georgia (UGA) College of Public Health, Department of Environmental Health Science. His recent areas of research include (1) an exposure assessment and epidemiological study of occupational fine inhalable particulate matter ($PM_{2.5}$) and carbon monoxide (CO) exposures (including biomarkers of exposure) and related respiratory health markers in southeastern U.S. forest firefighters; (2) an exposure assessment and epidemiological study of pregnant women and an occupational cohort investigating $PM_{2.5}$, CO, nitrogen dioxide, and volatile organic compounds exposures in air and environmental chemicals measured in blood and urine, and related respiratory health markers in Trujillo, Santiago de Chuco, San Marcos, Junin and Ayacucho, Peru; and (3) an exposure assessment and environmental epidemiological study of UGA students exposed to secondhand smoke in outdoor settings in Athens, Georgia. He is also currently a joint primary investigator on a National Institutes of Health Fogarty Regional GEO Health Hub Centered in Peru, and a co-investigator on The Household Air Pollution Intervention Network (HAPIN) Trial, which is an international multicenter study aimed at assessing the impact of a liquefied petroleum gas cooking stove and fuel intervention on health. HAPIN Trial centers are located in four countries: Guatemala, India, Peru, and Rwanda. Dr. Naeher received his Ph.D. in epidemiology and public health from Yale University.

Carsten Warneke is a senior research scientist at the National Oceanic and Atmospheric Administration (NOAA) Chemical Sciences Laboratory. He is the leader of the Volatile Organic Compound (VOC) group and responsible for planning and leading large-scale NOAA field experiments for air quality and climate research. He is currently one of the principal investigators of the upcoming NOAA Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas 2023 field experiments looking at air quality in urban areas and most notably principal investigator of the NOAA/National Aeronautics and Space Administration-led Fire Influence on Regional to Global Environments and Air Quality campaign, which is a multiyear, multiagency measurement campaign focused on the impact of fires on climate and air quality from western North American wild fires and southeastern prescribed and agricultural fires. His main expertise is in air pollution on regional to global scales, and his focus lies on the science of VOCs in the atmosphere. Dr. Warneke received a Ph.D. in physics from the University of Innsbruck, Austria, in 1998. Afterwards he spent 3 years as a post-doc at the University of Utrecht, Netherlands, before moving to the University of Colorado Boulder, and the NOAA Chemical Sciences Laboratory in Boulder in 2001.

Christine Wiedinmyer is the associate director for science at the University of Colorado Boulder's Cooperative Institute for Research in Environmental Sciences. A former scientist at the National Center for Atmospheric Research (NCAR), Dr. Wiedinmyer holds a bachelor of science in chemical engineering from Tulane University and a Ph.D. in chemical engineering from the University of Texas at Austin. Dr. Wiedinmyer's research focuses on the identification and quantification of various emission sources and modeling the transport and fate of emitted pollutants in the atmosphere. She is the creator of the Fire INventory from NCAR (FINN) model that estimates emissions of pollutants from open burning globally; the FINN emissions estimates have been applied in numerous air quality and climate studies to evaluate their impacts. Furthermore, Dr. Wiedinmyer is an expert in interdisciplinary research to connect her research to other areas of societal relevance, such as public health, land management, and climate. She is the recipient of the Walter Orr Roberts Lecturer for Interdisciplinary Sciences from the American Meteorological Society in 2014 "for research on biomass burning and its impact on the atmosphere and terrestrial biosphere, and bridging atmospheric science, biology, engineering, public health and other disciplines." Dr. Wiedinmyer is also a founding member and a current board member of the Earth Science Women's Network. Dr. Wiedinmyer was a member of the National Academies of Sciences, Engineering, and Medicine's Committee on the Future of Atmospheric Chemistry Research, January 2015 to August 2016.

Appendix C: Workshop Agenda

Wildland Fires: Toward Improved Understanding and Forecasting
of Air Quality Impacts – A Workshop

September 23-25, 2020
Public Agenda

Virtual

All times are EDT

Workshop Goal: To bring together atmospheric chemistry and health research communities, managers, and decision makers to discuss knowledge and needs surrounding how wildfire effluent affects air quality and human health. Interdisciplinary sessions will allow for exploration of opportunities to better bridge these communities, to advance the science and improve the production and exchange of information.

Day 1: Wednesday, September 23, 2020

1:00 PM Welcome and introductions
Ravi Ravishankara, Committee Chair, Colorado State University

1:10 PM Keynote
John Balmes, University of California, San Francisco

Session 1: Where Are We Now?

This session will set the stage for the workshop, providing overviews of the current state of the science and communication around atmospheric chemistry and transport of fire emissions, forecasting, measurement tools, and smoke health effects.

Moderator: **Christine Wiedinmyer**, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder
Monitor: **Carsten Warneke**, National Oceanic and Atmospheric Administration (NOAA) and CIRES

1:35 PM Our changing fire regimes
Jennifer Balch, University of Colorado Boulder

1:50 PM Fire structure, real plumes, and models
Brian Potter, U.S. Department of Agriculture (USDA) Forest Service

2:05 PM Panel: How well can we predict smoke?
Brief panelist remarks followed by moderated Q&A

Moderator: **Carsten Warneke**, NOAA/CIRES
Monitor: **Sim Larkin,** USDA Forest Service

Ravan Ahmadov, CIRES/NOAA
James Crawford, National Aeronautics and Space Administration
Brad Pierce, University of Wisconsin
Kirk Baker, U.S. Environmental Protection Agency (EPA)

3:10 PM Break

3:40 PM Can understanding combustion chemistry improve air quality forecasting?
Bob Yokelson, University of Montana

3:55 PM How does smoke change as it travels away from the source?
Emily Fischer, Colorado State University

4:10 PM What are some health effects of smoke?
Colleen Reid, University of Colorado Boulder

4:25 PM Panel: What information is currently being communicated between health and atmospheric chemistry communities?
Brief panelist remarks followed by moderated Q&A

Moderator: **Susan Anenberg**, George Washington University
Monitor: **Michael Benjamin**, California Air Resources Board

Ana Rappold, U.S. EPA
Nga Lee Ng, Georgia Institute of Technology
Rish Vaidyanathan, U.S. Centers for Disease Control and Prevention

5:25 PM Final thoughts, plan for day 2
Ravi Ravishankara, Colorado State University

5:30 PM Adjourn

Day 2: Thursday, September 24, 2020

1:00 PM Introduction to day 2 agenda
Ravi Ravishankara, Committee Chair, Colorado State University

1:10 PM Summary of ideas heard on day 1
Susan Anenberg, George Washington University, on behalf of the planning committee

Session 2: Where Do We Want to Be?

This session will focus on what is needed on the ground and how that translates into primary research needs within the atmospheric chemistry and health communities to better protect air quality and human health. What do we need to learn about air quality to mitigate, manage, and prevent health effects?

Moderator: **Luke Naeher**, University of Georgia
Monitor: **Christine Wiedinmyer,** CIRES, University of Colorado Boulder

1:40 PM What is needed to mitigate health effects from a public health decision maker perspective
Sarah Coefield, Missoula City-County Health Department

1:55 PM Improving understanding to reduce health effects from a toxicologist perspective
Michael Kleinman, University of California, Irvine

2:10 PM Break

2:45 PM Panel: Mitigation and management needs from other health and regulatory perspectives
Brief panelist remarks followed by moderated Q&A

Moderator: **Susan Anenberg**, George Washington University
Monitor: **Carsten Warneke**, NOAA/CIRES

John Stromberg, Mayor, Ashland, Oregon
Lee Newman, Colorado School of Public Health and School of Medicine
Olorunfemi Adetona, The Ohio State University
Dana Skelly, USDA Forest Service
Michael Benjamin, California Air Resources Board

4:00 PM	Links between wildfire, air quality, and COVID-19 **Sarah Henderson**, British Columbia Centre for Disease Control
4:25 PM	Final thoughts, plan for day 3 **Ravi Ravishankara**, Colorado State University
4:30 PM	Adjourn

Day 3: Friday, September 25, 2020

1:00 PM	Introduction to day 3 agenda **Ravi Ravishankara**, Committee Chair, Colorado State University
1:10 PM	Summary of ideas heard on day 2 **Christine Wiedinmyer**, CIRES, University of Colorado Boulder, on behalf of the planning committee
1:40 PM	Keynote **Mary Nichols,** Chair, California Air Resources Board

Session 3: How Do We Get There?

This session will explore how we can improve the production and exchange of information about air quality and health effects between atmospheric and health communities and more broadly, as we look to future needs and capabilities for research and mitigation of health impacts.

2:00 PM	Panel: How do we get the information that is needed and anticipated in the future (5 years, 10 years)? *Brief panelist remarks followed by moderated Q&A* Moderators: **Sim Larkin**, USDA Forest Service and **Luke Naeher**, University of Georgia Monitor: **Carsten Warneke**, NOAA/CIRES **Sheryl Magzamen**, Colorado State University **Tim Reinhardt**, Wood Environment & Infrastructure Solutions, Inc. **Dan Jaffe**, University of Washington **Yang Liu**, Emory University
3:00 PM	Break

3:30 PM How do we improve information exchange for the future?
Short talks followed by moderated Q&A

Moderator: **Michael Benjamin**, California Air Resources Board
Monitor: **Susan Anenberg**, George Washington University

Pete Lahm, USDA Forest Service
Susan Stone, U.S. EPA
Michael Brauer, University of British Columbia
Marshall Shepherd, University of Georgia

4:45 PM Closing remarks
Workshop planning committee, led by **Ravi Ravishankara**

5:00 PM Adjourn